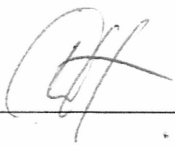
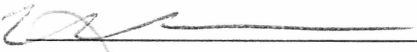
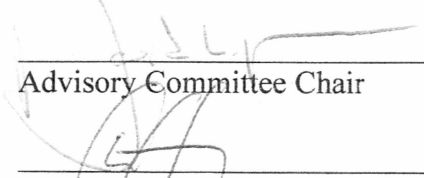


ESTIMATING SEASONAL AND DIURNAL VARIATIONS IN INFLUENT
WASTEWATER CHARACTERISTICS FOR OPTIMIZATION OF ACTIVATED
SLUDGE SYSTEM IN A NORTHERN COMMUNITY

By

Ameet John Pinto

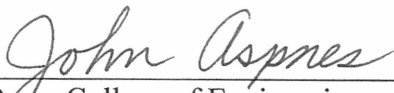
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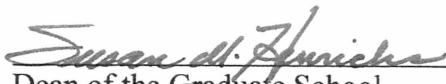




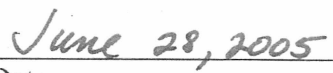
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WASTEWATER CHARACTERISTICS FOR OPTIMIZATION OF ACTIVATED
SLUDGE SYSTEM IN A NORTHERN COMMUNITY

A
THESIS

Presented to the Faculty
of the University of Alaska Fairbanks
in Partial Fulfillment of Requirements
for the Degree of

MASTER OF SCIENCE

By

Ameet John Pinto, B. Chem. Engg

Fairbanks, Alaska

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Abstract

Influent characterization experiments were carried out at the wastewater treatment facility in Fairbanks, Alaska. These experiments were carried out to trace the diurnal and seasonal variations in the influent flow and organic loading rates. A considerable difference in the wastewater flow and organic loading rates was seen on a seasonal as well as a diurnal basis. The project hypothesized that better understanding of broad influent diurnal and seasonal variations in a wastewater treatment facility can help optimize control strategies. Based on the observed variations, oxygen production and supply was analyzed as an avenue for optimization in the high purity oxygen activated system. The results indicate that up to 35% excess oxygen was being supplied on the sampling days despite the current control strategy. This excess may be eliminated by including an upstream measurement device in the treatment scheme to enhance control over the process. Respirometry may improve the plant's ability to make suitable predictions for the oxygen requirements. Benefits of respirometry were discussed and several site-specific recommendations were made for the application of respirometric techniques at the Fairbanks wastewater treatment facility.

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1. Introduction

The design and operation of many engineering systems assume a steady state operation. Over a large variety of engineered systems, especially industrial, the assumption of steady state holds true. However, certain systems cannot be considered steady state due to the lack of able control systems, unpredictable variations in operational conditions, and changing input variables. A domestic municipal wastewater treatment facility is one such example. The probability of achieving steady state in a biological wastewater treatment process, such as activated sludge, is low. The important input variables are influent flow rate, organic loading, and oxygen demand. These parameters depend on the activities of the community that the facility serves. The system itself can react unfavorably to changes in input variables because it is a biologically dependent process. To facilitate the optimal operation of a system designed for steady state conditions, it is important to estimate, understand, and predict the variations that are experienced by the facility.

A typical wastewater treatment facility (WWTF) experiences variations in the influent loadings and flow rates. For a facility that treats domestic waste, the variations are exhibited regularly on a diurnal basis as seen in Figure 1. Certain facilities may also experience variations on a seasonal basis. Such variations can be substantial due to dry and wet seasons. In certain cases, the wastewater flow in the wet season can be six- to ten-fold higher than the flow in the dry season (USEPA, 1981). Another reason for seasonal variations can be a change in population and community activities. On occasion, the influent amount being treated by a facility is referred to as a population equivalent

(PE).

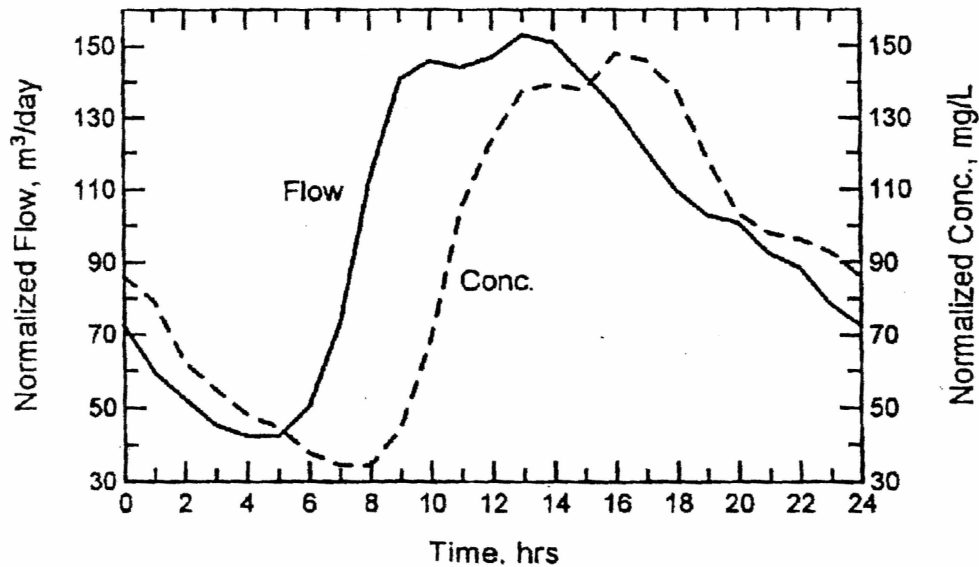


Figure 1: Variations in flow rate and concentration experienced by WWTF (Grady et al., 1999)

Adaptability of a system depends largely on the availability and the use of control systems. These control systems can be feed-forward or feed-back in nature. Feed-forward control strategy implies that suitable changes are made to the system parameters to deal with input variabilities. Feed-back control strategy implies that effects of input variabilities are measured at the output and then suitable changes are made. The application of feed-back control strategies is very prevalent in a WWTF, with emphasis on effluent quality check and control. However, the application of control strategies towards cost optimization is imperative as facilities can have substantial operating costs. The key to optimizing and controlling the activated sludge process lies in maintaining process stability. While the activated sludge process is central to the treatment scheme, the process is inherently unstable and can be easily upset (Cuny, 1979).

This project focuses on the Fairbanks WWTF owned and operated by Golden Heart Utilities. The primary objective of this project was to investigate the benefits of improved process control at a WWTF. The purpose of this can be outlined by the following points: (1) estimate the diurnal and seasonal variation in the waste strength and waste flows in Fairbanks, Alaska, (2) predict the required aeration rate required to treat this waste strength with respect to diurnal and seasonal variation, and (3) investigate the benefits resulting from adapting the aeration rate to diurnal and seasonal changes in waste strength. The hypothesis of this project is that:

Better understanding of broad influent diurnal and seasonal variations experienced by an activated sludge system can help optimize current control strategies at the wastewater treatment facility at Fairbanks, Alaska .

To test this hypothesis, diurnal and seasonal variations in the key influent parameters were fully characterized. The parameters were measured on raw influent and return activated sludge (RAS). The sample collection and analyses is explained in detail in Chapter 3.

Several operational variabilities, ranging from climatological conditions to the proportion of septic dumping in the influent line, make the Fairbanks treatment facility unique. This uniqueness is discussed in detail in the following chapters. The project concentrates on increasing the adaptability of the plant to diurnal and seasonal variations, which may

result in a decrease in current operational expenditure. Aeration control was chosen from the different options for optimization, as it is the most expensive unit operation in an activated sludge process. The production and use of pure oxygen in a high purity oxygen activated system (HPOAS) makes aeration expenses at the Fairbanks facility even more significant. The choice of control strategy and its possible application are discussed in detail in the following chapters. A corollary is making suitable observations and recommendations regarding efficient control strategy implementation at the wastewater treatment plant, within the scope of the project.

2. Literature Review

2.1 Activated Sludge Process and the High Purity Oxygen Activated Sludge System

The activated sludge system was conceived by Arden and Lockett in 1914. It is the most widely used biological wastewater treatment process. The basic process can be defined by four stages: (1) in what is called a bioreactor, a flocculent slurry of microorganisms is used to convert the soluble organic matter from influent wastewater into cell mass and carbon dioxide (CO_2), (2) in a clarifier settling is used to remove this slurry of microorganisms, referred to as mixed liquor suspended solids (MLSS), from the treated waste, (3) settled solids are recycled as a concentrated slurry from the clarifier back to the bioreactor, and (4) excess solids are wasted to control the age of the microorganisms (Grady et al., 1999). Figure 2 depicts how these functions are performed.

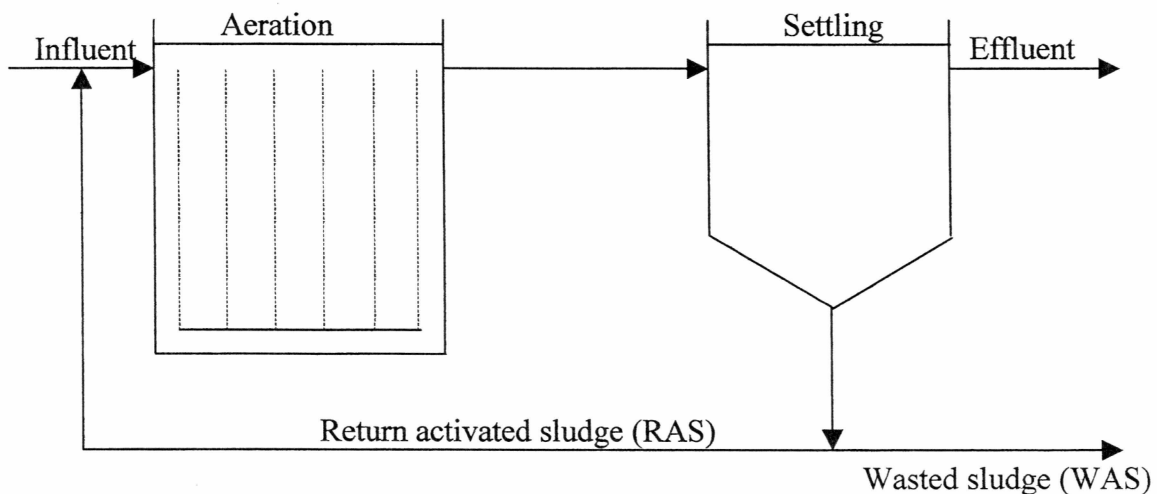


Figure 2: Schematic of a typical activated sludge process

The flocculent slurry of microorganisms is referred to as activated sludge. It is a heterogeneous microbial culture of bacteria, protozoa, rotifers, and fungi. However, it is

the bacteria that are responsible for most of the reduction of the organic matter (Benefield et al., 1980).

A traditional activated sludge process consists of two separate units - an aerated bioreactor system and a clarifier. A typical aeration process is a suspended growth type, in which the biomass is completely suspended in the liquid medium. The influent is mixed with the return activated sludge (RAS) from the recycle line and delivered to the reactor for aeration. With the aid of mixing, the RAS is blended with the influent. This mixture is called the mixed liquor. The mixed liquor suspended solids (MLSS) for a conventional activated sludge process may vary between 2000 to 4000 mg/l (Tchobanoglous et al., 2003). Aeration is accomplished using blowers pumping air into the system. It is of critical importance to obtain good mixing conditions to create maximum interfacial area between the gas and the liquid phase. Certain systems depend solely on the sparging of air to generate contact between gas and liquid phase, and also to keep the sludge in suspension. Other systems may depend on ancillary turbines for appropriate mixing. The mixed liquor then flows into a clarifier, where the sludge is gravity-settled, and the effluent overflows with low suspended solids and acceptable organic loading as defined by its five day biochemical oxygen demand (BOD_5) value.

There have been several modifications in the operation of the activated sludge system since its inception. Each modification is directed at making the process more efficient, and also addressing specific goals of constituent removal. One of the modifications is the

high-purity oxygen activated sludge (HPOAS) systems developed in 1970's by Union Carbide. The system was called Unox. As compared to the use of air in a conventional activated sludge system, the HPOAS provides pure oxygen to the microorganisms. Figure 3 is a schematic of the HPOAS bioreactor.

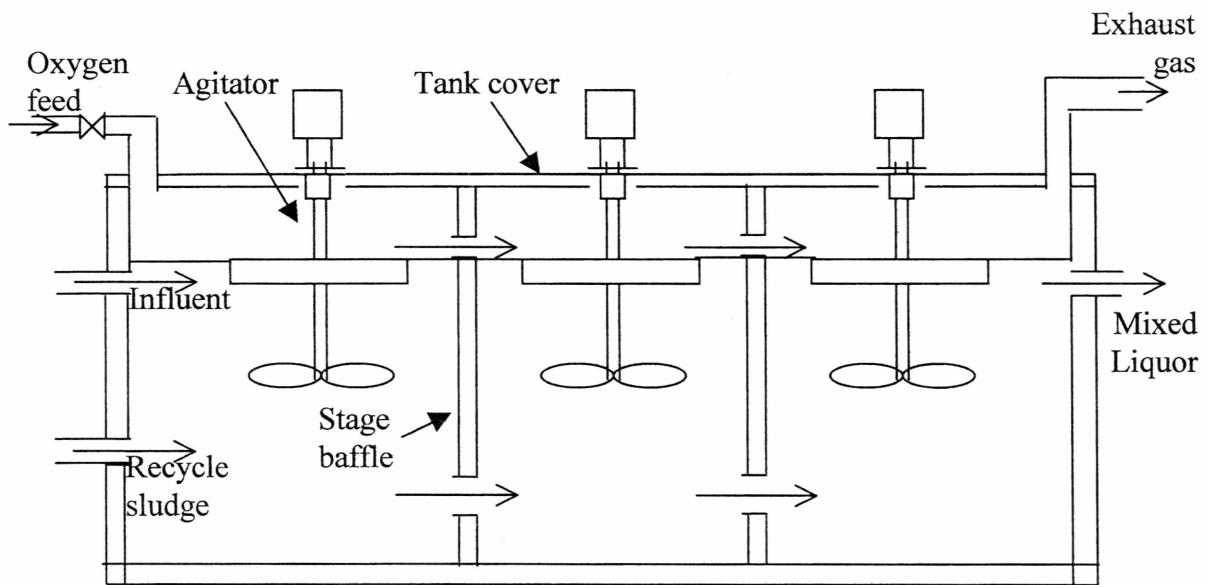


Figure 3: Typical cross section of a high-purity oxygen activated sludge (HPOAS) system showing 3 stages

HPOAS systems have certain advantages over a conventional system. The use of pure oxygen increases the partial pressure of gas in each stage. This increase in partial pressure improves the volumetric transfer rate of gas into the liquid phase. The importance of this lies in the fact that such high mass transfer rates will make oxygen readily available for uptake by microorganisms. Theoretically, the volumetric mass transfer rates for pure oxygen may be almost five times the transfer rates for air. This relatively high transfer rate reduces the hydraulic retention time (HRT) to between one to

five hours as compared to eight to ten hours for a conventional activated sludge system (Tchobanoglous et al., 2003).

Use of pure oxygen in a HPOAS system allows for a higher concentration of suspended solids into the aeration unit (USEPA, 1974). The high oxygen transfer rate is credited with this ability. The HPOAS system also exhibits a higher substrate utilization rate compared to a system supplied with air. The difference between an air-only system and a HPOAS system is that the air-only system is a large volume-low suspended solids system and the HPOAS system is a small volume-high suspended solids system. The flocs in the latter system are recycled much more frequently than those in the former, when operated at the same solids retention time (SRT). During the interval between recycle, the flocs use the substrate within the floc lattice, and on return, have a higher substrate utilization rate. Hence, the more frequent rate of recycle produces a higher rate of substrate utilization. The advantages of a HPOAS system over a typical air-only system can be listed as follows (Benefield et al., 1980):

- Capability to meet higher oxygen demands,
- Ability to maintain higher mixed liquor volatile suspended solids (MLVSS) in a smaller volume, and thus provide equivalent treatment in a small volume,
- Lower net sludge production per unit BOD₅ removed, and
- Higher oxygen transfer rate.

Most of the pure oxygen systems being implemented at an industrial scale are enclosed, as shown in Figure 3, to maintain a head space partial pressure of oxygen. The covered HPOAS systems also have disadvantages. The main disadvantage of this system is the buildup of carbon dioxide (CO_2) in the system. High CO_2 partial pressures result in a decrease in the pH of the system and are detrimental to nitrification. Another common disadvantage of the covered pure oxygen system is the need for prescreening to reduce the solids entering the system through the influent. Generally, the oxygen is supplied to the head space in the aeration chamber. Transfer of oxygen into the liquid phase is dependent on mixing by turbines, and on the high partial pressure of oxygen. The need for a high rate of mixing results in substantial shear from the impellers resulting in poor settling characteristics (USEPA, 1974). Sludge being generated by a HPOAS system is treated in the same way as that from any conventional activated sludge system. The general options for the treatment of the biosolids generated are aerobic digestion, anaerobic digestion, thickening, composting, and dewatering (Tchobanoglous et al., 2003).

Typically, plants with a pure oxygen system generate the oxygen onsite. Oxygen required at these facilities is in tonnage quantities, and it is not economically feasible to buy this quantity of oxygen on a regular basis. The first industrial scale applications of the HPOAS systems in the 1970's started with the development of the pressure swing adsorption (PSA) method to produce pure oxygen on site (USEPA, 1974). The use of PSA for on-site production is three to four times cheaper than buying liquid oxygen in

tankers. Air contains 78% nitrogen, 21% oxygen, and 1% is other gases like argon, carbon dioxide, etc.

Under high pressure, the sieve in a PSA generator adsorbs nitrogen, and at low pressures nitrogen is desorbed. PSA generators consist of two tanks filled with sieves. Air is introduced under high pressure into the first tank, where the sieve adsorbs all the nitrogen. The remaining oxygen and other gases are piped to a buffer or a storage tank. Before the sieves in the first tank become completely saturated with nitrogen, the high pressure air feed is directed to the second tank, and the first tank is vented to the atmosphere. This venting desorbs the nitrogen. Then a small amount of oxygen is purged through the first tank to complete the process of sieve regeneration.

The productivity of a PSA generator is dependent on the oxygen purity required. A generator can produce significantly more oxygen at 90% purity than it can at 95.4%, with a relatively small increase in air feed. By means of a timing based controller, it is practical with larger generators for the user to change the swing cycles. Flow levels can be selected and optimized based on changing demand variables (Operators manual). The typical oxygen transfer rate (OTR) for a HPOAS with oxygen from PSA gas generation and surface aerators is about 1.22 kg O₂/ kWh (Vernick and Walker, 1980). The amount of energy required for a 38,000 m³/day plant is about 1.12×10^6 kWh/yr (Vernick and Walker, 1980).

2.2 Fairbanks WWTF and its Uniqueness

The extreme climatological conditions experienced in Fairbanks, Alaska have a strong influence on the community population and its dynamics. The temperature variation in Fairbanks can range from -60°C in the winter to 35°C in the summer. The temperature extremes are one reason that the WWTF is indoors. The wastewater temperatures may vary from 6°C in winter to 16°C in summer. There is also large variation in the daylight hours from summer (approximately 21 hours) to winter (approximately 3 hours). This affects the strength of the waste entering the plant during different times of the day due to the change in community activities over the seasons.

During the summer season, the population of Fairbanks is much larger than its usual winter and spring populations. The summer influx of tourists possibly impact the influent flows and the variation in the organic loadings experienced by the facility. Another seasonal impact on influent flows could be due to infiltration of groundwater into the sewer system during the summer and fall. The influent flow rates may change from $19,000\text{ m}^3/\text{day}$ in summer to about $11,500\text{ m}^3/\text{day}$ in the winter.

The Fairbanks WWTF operates a HPOAS treatment system. The source of the influent for this treatment facility is mostly domestic municipal waste. The aeration unit at the facility consists of two aerators, referred to as the south and the north aerators. Each of these aerators consists of four chambers. Oxygen required for the systems is manufactured onsite using the PSA technique. Adding the traditional aeration expenses

such as pumping and mixing, to the entire operation of the aeration train results in a higher percentage of the total operating cost of the plant, as compared to a typical activated sludge plant.

Another important uniqueness of the Fairbanks WWTF is the lack of a primary settler in the treatment scheme. A typical facility would consist of three different unit operations in advance of the HPOAS system. The raw influent is passed through mechanical bar screens, a grit chamber, and a primary sedimentation basin. Of the three, the primary sedimentation basin is of critical importance. Primary sedimentation can remove up to 40% of the influent chemical oxygen demand (COD) as particulate matter (Grady et al., 1999). If not removed, this 40% excess particulate COD enters the aeration train and is incorporated into the solids to be wasted. This particulate COD, which could well be inert material, now becomes a part of the active sludge. The treatment and disposal of the sludge is a cost intensive and labor intensive operation. At the Fairbanks WWTF, the biosolids are converted to compost and sold. Biosolids treatment costs are approximately \$100/ton (Urban, 2004).

The primary sedimentation tank can also act as an intermediate detention tank to increase the time between the introduction of the raw influent in the treatment scheme and the primary treated influent being introduced into the aeration tank. This detention time can be critical, as it can give the operator sufficient time to make adequate changes in the system, such as those required in a case of shock loadings. For the Fairbanks WWTF, the

time between the raw influent entering the treatment scheme and it entering the aeration train is only about five to six minutes. The ability to adapt to changes in influent flow and characteristics is important to any facility to accommodate diurnal and seasonal variations, and shock loadings.

Another result of the extreme cold conditions in Fairbanks is the frequency of septic waste dumping. Septic tanks are emptied in the summer when temperatures are warm, allowing biomass to accumulate prior to low winter temperatures. The amount of septic loads experienced by the facility in summer is almost five times of that in the fall. In winter there is little or no septic dumping.

Septic waste can have a substantial impact on an activated sludge system. Septic wastes consist of grease and scum found on the surface of septic tanks, the sludge and grit accumulated at the bottom, and sewage present at the bottom of the tank at the time of pumping (Borchardt et al., 1981). The ratios of nitrogen and phosphorus to carbon tend to be lower in septic waste than domestic wastewater, due to the utilization of these nutrients during anaerobic digestion (Segall et al., 1980). Being an anaerobic sludge, septic waste generates gaseous products. Hence, it has the ability to foam, and has poor settling and dewatering characteristics. The introduction of the septic waste with a high amount of settleable solids into a treatment scheme without a primary settler implies that all the settleable solids enter the aeration train. Domestic septic waste is about five times as strong as domestic wastewater (Segall et al., 1980). Including septic waste into the

treatment scheme with regular influent can raise the BOD_5 of the waste from normal values of 220 mg/l to values as high as 600 mg/l. Such high demands can easily upset the effluent quality standards that have been established. Dumping of deicing liquid from the Fairbanks International Airport into the influent line also affects effluent quality. The additives present in the deicing liquid poison the microbial culture used for wastewater treatment. Reduction in microbial activity results in decreased efficiency of the treatment system.

2.3 Process Control Strategies

Most activated sludge plants operate in a time-varying environment and their operating conditions may be significantly different from the original design specifications. This variation may reduce the treatment efficiency unless the plant operation is continually adjusted. Efficient handling of the influent variations dictates the implementation of sound process control strategies. The principal objectives of process control in the activated sludge process are damping out of any variation in the input, minimization of effluent variation, and prevention and recovery from process upsets (Schroeder, 1983). Another important objective of process control is to make the process cost efficient. The obstacles that any process control strategy would need to overcome are large variations of input organic loading, variations of sludge inventory and hence of sludge kinetics, and limited availability of on-line process measurements (Stefano, 1989).

Of all the different units that comprise the activated sludge system, the most sensitive and important unit is the aeration train. The aeration train is the target unit in which several effluent quality requirements are met. Reductions in organic loading and reduction in the nitrogenous content are two of the important objectives met in the aeration train. It is important to recognize the different key input parameters that eventually affect the performance of this critical unit. These input parameters will be addressed as the controllable parameters. Arthur (1983) lists the controllable elements in a typical activated sludge process as control of wasting, control of sludge return, and control of aeration. The parameters and possible positions of their measurement and control are indicated in Figure 4. Primary and secondary clarifiers are denoted by P.C. and S.C., respectively.

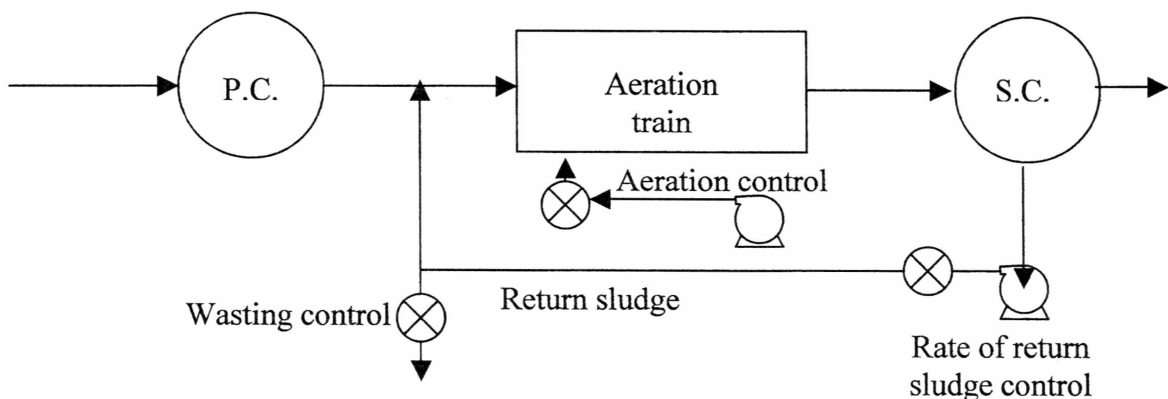


Figure 4: Controllable variables in activated sludge systems (Arthur, 1983)

The control of sludge wasting rate, rate of return sludge, and aeration has certain primary reasons, and alternate benefits. The control of aeration or oxygen supply is primarily meant to reduce the organic loading. This control is also yielded in such a way that the

dissolved oxygen in the mixed liquor is always maintained above 2.0 mg/l. The rate of return sludge control is maintained to provide sufficient microbes to degrade the influent to the required standard. The wasting control is meant to control the age of the sludge.

All control strategies can be broadly categorized into feed-forward or feed-back control strategies. Feed-forward control strategies require continuous information on the variation of input variables. Depending on these input variations, changes are made to process control parameters to maintain the quality of the output at a set level. Conversely, feed-back control strategies require continuous information on the output variables. The deviation of the output variables from their set point dictates the changes that need to be made in the process control parameters. Sometimes the performance of the process is dictated by biological performance indicators that have been established in the wastewater industry on the operation of an aeration train.

2.3.1 Sludge Age Control

One such biological performance indicator is the sludge age in the aeration unit. The sludge age may be maintained at a specific set value by controlling the wasting rate of the settled sludge. The primary reason for maintaining the solids retention time of the system and wasting solids is to maintain the entire microbial culture at a constant metabolic rate by keeping their age constant, and wasting dead cells and trapped inorganic matter. However, sludge wasting has other advantages as listed by Arthur (1982):

- Reduces the number of viable microorganisms and decreases the oxygen requirements during endogenous respiration,
- Removes microorganisms that create poor settling sludge, the filamentous species,
- Reduces the total suspended solids concentration to improve mixing, and
- Maintains a balance between inorganic-organic matter, and viable microorganisms.

The sludge age is also referred to as the solids residence time (SRT) and it is defined by (Tchobanoglous et al., 2003):

$$SRT = \frac{\text{Bacterial mass in the aerator}}{\text{Bacterial mass wasted daily}} = \frac{VX}{(Q - Q_w)X_r + QX_e} \quad (1)$$

where V is the volume of the aeration unit, X is the biomass concentration in the aerator, Q is the system flow rate, Q_w is the wasting rate, X_r is the biomass concentration in the recycle stream, and X_e is the biomass concentration in the effluent stream.

Sludge age control is an important parameter because it is related to the growth rate and the BOD₅ removal rate. The sludge age determines the metabolic activity of the microbial mass responsible for BOD₅ removal. The SRT value and the effluent organic loading are directly related to each other by the following relationship (Tchobanoglous et al., 2003):

$$S = \frac{K_s [1 + (k_d SRT)]}{SRT(\mu_m - k_d) - 1} \quad (2)$$

where S is the effluent BOD_5 concentration, SRT is the solids residence time, K_S is the half saturation concentration, k_d is the decay co-efficient, and μ_m is the maximum specific growth rate. Thus, the maintenance of good effluent quality is strongly dependent on the sludge age. Process design specifications and field study data provide guidance for the SRT for the optimum efficiency of a given system. Different values have been indicated in the literature for a wide variety of aeration units and treatment scheme (Grady et al., 1999; Tchobanoglous et al., 2003). Typically, the SRT values for most systems will vary between three to five days, with a shorter range of one to five days for a HPOAS system such as the one used at the Fairbanks WWTF. The SRT is controlled by controlling the sludge wasting rate (Q_w).

2.3.2 F:M Control

Another important biological process indicator is the food to microorganism ratio. The food-to-microorganism ratio can be defined as:

$$F:M = \frac{\text{Substrate mass utilized in 24 hr}}{\text{Bacterial mass in the aerator}} = \frac{\int_0^{24} (S_i - S) dt}{VX} \quad (3)$$

where S_i is the influent substrate concentration, S is the effluent substrate concentration, V is the volume of the aeration unit, and X is the biomass concentration in the aerator. The substrate influent concentrations may be expressed as BOD_5 or COD.

The $F:M$ is usually defined as mg/l of organic loading per mg/l of the mixed liquor volatile suspended solids (MLVSS) and is used to determine if the aerator is under-

loaded or over-loaded. An under-loaded system means a low F:M value in the aeration unit leading to a famine situation (lack of food), and an over-loaded system means a high value which causes a feast situation (surplus of food). Similar to the SRT, the values for F:M ratios are dependent on the type of equipment being used, and there are several literature reported values. The F:M ratio should have a maximum range between 0.1 and 1.0 for efficient operation (Tchobanoglous et al., 2003). The Fairbanks WWTF is designed to operate efficiently for an F:M ratio between 0.4 and 0.6 (Operators Manual).

A limitation of the F:M ratio is the use of a MLVSS value as a quantifier of the viable organisms in the microbial biomass (Arthur, 1982). Mixed liquor volatile suspended solids is an easily measurable quantity that includes the active biomass or viable microorganisms, cell debris resulting from cell death, and other non-biodegradable volatile suspended solids that are introduced through the influent. A correct measure of the F:M would include only the viable organisms in the ratio. The amount of active biomass can be determined by respirometric methods as reported by Nicols (1982). The following equation gives the concentration of viable organisms in the microbial mass:

$$ViableOrganism(VO) = (OUR - RAS) \times \frac{QRAS}{Q + QRAS} \quad (4)$$

where OUR-RAS is the respiration rate of return activated sludge, QRAS is the return activated sludge flow, Q is the influent wastewater flow. Nicols (1982) also defined the viability factor of the activated sludge as:

$$ViabilityFactor(VF) = \frac{(OUR - RAS)}{RSS} \quad (5)$$

where RSS is the return activated sludge suspended solids concentration.

Such an understanding of the viability of the activated sludge should provide for a better control on the F:M ratio. Arthur (1982) pointed out that the use of BOD₅ is inaccurate, since it does not provide appropriate information about the food entering the aeration scheme and the five-day delay in test results does not provide timely information for process control. Nicols (1982) provides an alternative respirometric measure of food (F).

$$F = (OUR - I) - VO \quad (6)$$

Where (OUR-I) is the oxygen uptake rate of the initial mixture of return activated sludge and wastewater.

The F:M ratio presented by Arthur (1982) is:

$$\frac{F}{M_{(VO)}} = \frac{[(OUR - I) \times (Q + QRAS)] - [(OUR - RAS) \times QRAS]}{(OUR - RAS) \times QRAS} \quad (7)$$

An accurate F:M ratio should help predict the wasting rate more precisely. The sludge recycle at the Fairbanks facility varies between 40-60% of the influent flow rate depending on the expected organic loading. This 40-60% recycle is believed to provide an acceptable F:M for efficient operation.

2.3.3 Dissolved Oxygen (DO) Control

Dissolved oxygen (DO) is the required electron acceptor in the aerobic biological oxidation reactions of activated sludge treatment. DO control is the most studied aspect of the activated sludge process control automation. The type of DO control being applied

in a WWTF depends on the type of the reactor being used. DO probe measurements can be taken at specified location along the length of the aeration train. Depending on the measured DO concentrations, a feed-back control system manipulates the aeration rate. In a complete mix plant only the DO level will be controlled, where as in a plant using a longitudinal plug flow reactor, the shape of the DO profile will also be controlled. The liquor exiting the aeration tank should have a minimum DO of 1.5 to 2.0 mg/l. Biological oxidation of the carbonaceous substrate occurs when the DO levels in the liquor are above a threshold of 1.0 mg/l (Stefano, 1989). This control ensures that the effluent is aerobic.

The lack of DO will lead to anaerobic conditions altering the settling characteristics, which in turn can result in an increase in the TSS of the effluent (Sezgin et al., 1978). The OUR of wastewater varies due to the variation in organic loading. Due to this heterogeneity, a constant DO level ensures that the oxygen demand of the influent is being met and aerobic conditions are being maintained. Precise DO control has advantages such as assuring good sludge quality, making available the right quantity of oxygen needed by a time-varying biochemical demand and avoiding unnecessary energy expenditure (Arthur and Arthur, 1994; Prakasam et al., 2000). The DO is usually controlled by a feed-back loop with data provided by DO probes installed into the aeration train at specific locations depending on its construction and type. This control can be automated or manual. Automated systems are similar to building a temperature control in a room using a thermostat. Depending on the difference between the set point

for the DO and the actual DO, oxygen supply will be increased or decreased. At the Fairbanks facility, the DO level in the last chamber of the aeration train is checked every five to six hours, and the aeration rate is adjusted with reference to the measured DO.

DO measurements for controlling the aeration is a feed-back control strategy. Activated sludge treatment in a conventional system can be a slow process, with hydraulic residence time (HRT) in the aeration train varying from eight to ten hours (Benefield et al., 1980). For long HRT values the nature of the waste could change drastically before a control action can be made. In such cases a feed-back control system would be of minimal use. Prakasam et al. (2000) reports a 10 to 58% cost savings for certain cases using a DO probe control system. However, on the whole, a feed-back control strategy is directed towards effluent quality and sludge health maintenance purposes rather than cost efficient operational purposes.

Anticipatory control of aeration depending on the organic loading of the influent is an active feed-forward control strategy. The need for an active strategy arises from the fact that aeration is the most important and energy consuming operation in an activated sludge process. It accounts for 45 to 75% of the total electricity consumption at a modern activated sludge plant. Prakasam et al. (2000) reports that by the year 2010 the aeration electricity usage nationwide will be between approximately \$565 million and \$940 million per year at a unit cost of \$0.05 kWh. Electricity consumption is reflected in the high air pumping rates that are maintained.

Change in aeration rates with change in organic loadings has long been recognized as a possible source of cost savings. Control systems have been designed to meet these requirements. One such control involves the dependence on arbitrary means such as monitoring of oxidation-reduction potential (Charpentier et al., 1989). Use of respirometry also has potential. Respirometry can constantly monitor the influent to the treatment process. Such an upstream respirometric analysis can enable an anticipatory change in the aeration rate. Arthur and Arthur (1994) reports a 15 to 40% cost savings as a result of such anticipatory control.

Arthur (1982) suggests the required air flow rate for adequate aeration as:

$$Q_{AIR} = \frac{1.114 \times 10^{-5} OUR}{E} \quad (8)$$

where Q_{AIR} is the amount of air required ($\text{ft}^3/\text{min}/$ gallon of wastewater), OUR is the oxygen uptake rate of the wastewater (ml/l/hr), and E is the oxygen transfer efficiency (%). The absence of aeration requirements to meet the nitrogenous demand is the oversight of this prediction (Arthur, 1982).

Choosing criteria and employing them for control purposes, such as previously discussed, is a very important task. In a WWTF, such decisions are taken by the facility operators. Any control strategy employed must not only be theoretically sound, but also must be easy to employ, time conservative in nature, and beneficial. Selection of a control strategy is a largely site specific process.

Modeling programs used to simulate the wastewater treatment process also help evaluate the capital and operating costs of the treatment scheme. One such simulation program GPS-X estimates the cost functions as follows (Buys et al., 1998):

$$F = U (K_{org} \cdot f(Q, SS, BOD_5, COD) + K_{nutr} \cdot f(Q, P, N)) + E \cdot f(k_L a) \quad (9)$$

where U is the pollution unit fine (capital/yr), E is the electricity cost (capital/kWh), K_{org} and K_{nutr} are the weighting factors for organic and nutrient pollution. The operating cost is a function of flow rate (Q), suspended solids (SS), BOD_5 , and COD (effluent properties). The second term in the operating cost is the amount of energy exerted to treat the waste. The mass transfer co-efficient for transfer of oxygen from gas to the liquor is denoted by $k_L a$, which accounts for the aeration rate as well as the mixing (if required). The equation thus has two important parts to it, one of them being exclusive to the operation of aeration. Figure 5 shows that of all the different operating costs in a conventional activated sludge system, indicates that aeration is the most expensive process.

The amount of energy spent for aeration is very high compared to other sources of electrical expenses. The importance of this factor is further compounded by the fact that some facilities, like the Fairbanks WWTF, use pure oxygen rather than air and depend on turbine induced energy for mixing. Certain facilities, especially those that use aerating systems like air diffusers, depend on aeration to create a sufficient interfacial area to

facilitate high oxygen transfer rates. These facilities use air instead of pure oxygen. A change in aeration rate for these type facilities may not be the best option, as it would compromise on the rate of mixing. Such a control strategy is optimal for a HPOAS systems, like the one at the Fairbanks WWTF. Such facilities do not depend on aeration to provide mixing. Mass transfer is enhanced in HPOAS systems due to the purity of oxygen and extra agitation involving the use of turbines.

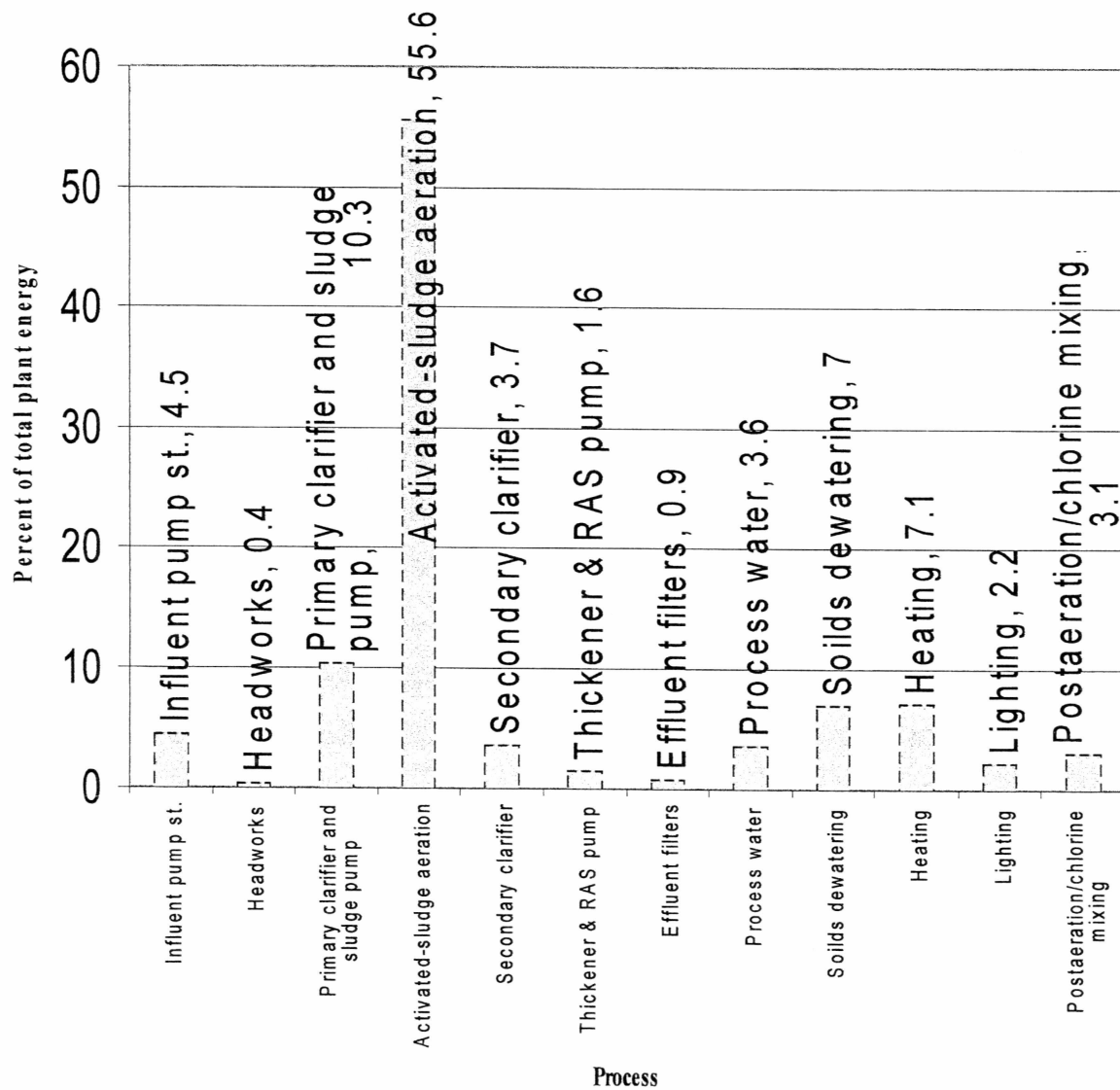


Fig. 5: The energy distributions for different operations (Tchobanoglous et al., 2003)

3. Materials and Methodology

Wastewater sampling was conducted at the Fairbanks WWTF in two phases. The first phase of the sampling was referred to as the initial sampling and the second phase was referred to as the 24 hour sampling. The initial samplings were carried out in July 2004. Initial sampling data were aimed at providing the following information: variations in wastewater characteristics over different times of day, properties of the RAS, and the change in loadings due to the introduction of septic waste into the treatment system. Initial sampling was conducted at specific times over a period of five consecutive days representing a typical work week. All 24 hours of the day were accounted for. It was assumed that over the period of five working days, community activity tended to remain similar. All the tests were started within 30 minutes of sample collection. Thus, no sample preservation was required.

The second set of experiments was carried out on three different dates in 2004 (July 21st, August 22nd, and November 2nd). These dates were selected to represent a particular season such as summer, fall, and winter. Samples were collected at two hour intervals. In addition, samples were collected over 24 hours to represent the diurnal variations occurring on that day. On two of these days BOD₂₀ was also measured. The BOD₂₀ was measured to include the nitrogenous demand. This measurement of nitrogenous demand was of particular interest due to the inability of the present system to reduce ammonia levels in the wastewater.

The following tests were conducted on the influent: total suspended solids (TSS), volatile suspended solids (VSS), five day biochemical oxygen demand (BOD₅), 20-day biochemical oxygen demand (BOD₂₀), ammonia-nitrogen (NH₄-N) measurement, temperature, pH. All the experimental procedures were conducted according to the Standard Methods (1998). The NH₄-N analysis was carried out using Hach high range (0-50 mg/l) ammonia test kits, as they are Environmental Protection Agency (EPA) approved for WWTFs. The return RAS was tested for the following characteristics: TSS, VSS, and pH. Table 1 lists the different standard laboratory techniques used with their referred test number as provided by Standard Methods (1998) and EPA.

Table 1: Standard Methods (1998) tests and the test numbers

| Test | Test number |
|------------------------------------|-----------------------|
| Five day biochemical oxygen demand | Standard Method 5210B |
| Total suspended solids | Standard Method 2540D |
| Volatile suspended solids | Standard Method 2540E |
| Ammonia-Nitrogen level | EPA 350.2 |

Whatman glass microfibre filters (GF/C) were used for TSS and VSS analysis. The chemicals used for the BOD₅ were in compliance with standard methods. 2-chloro-6-(trichloromethyl) pyridine (TCMP) was used as the nitrification inhibition agent for the BOD₅ tests. Nitrification inhibition ensures that the entire oxygen demand exerted in five days would be purely carbonaceous in nature. No nitrification inhibitor was used for the

BOD₂₀ tests. The samples were not seeded, as all the sampling was done at the primary influent inlet, except for the RAS which was sampled at the recycle line. The dilution water for the five day tests was prepared using Hach nutrient buffer pillows.

4. Results

The following graphs illustrate the variation in influent characteristics over the period of a day, on three different sampling days (July 21st, August 22nd, and November 2nd).

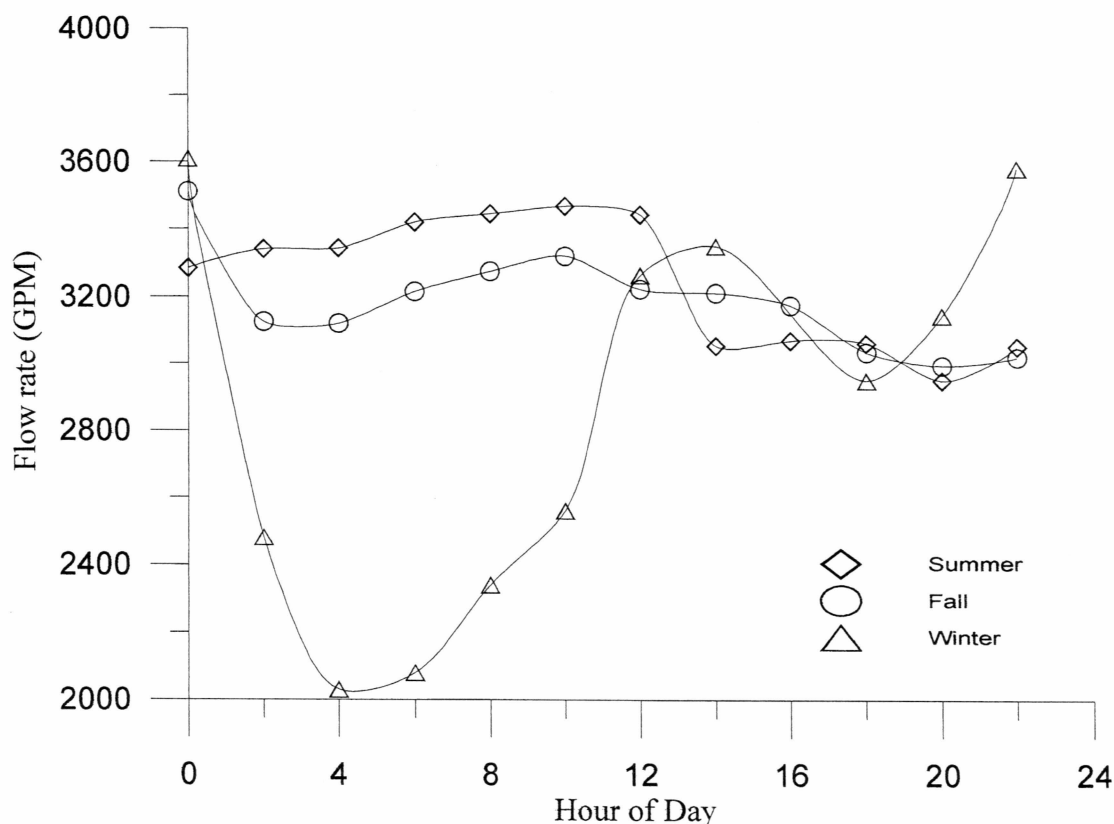


Figure 6: Variation in influent flow rate with hour of day

The flow rates, shown in Figure 6, experienced by the WWTF over the period of the day varied significantly from a low of 2,000 gallons per minute (GPM) to about 3,600 GPM. The extent of variation was far more severe in winter as compared to summer and fall. Total influent flow experienced by the treatment plant in winter is lower than summer or fall. Treatment scheme operational flows were 4.67 million gallons per day (MGD) (17,800 m³/day) in the summer, 4.58 MGD (17,450 m³/day) in the fall, and 3.77 MGD (14,380 m³/day) in the winter.

A diurnal variation is also seen in the BOD_5 values of the influent due to corresponding variability in human activity. This variation is shown in Figure 7.

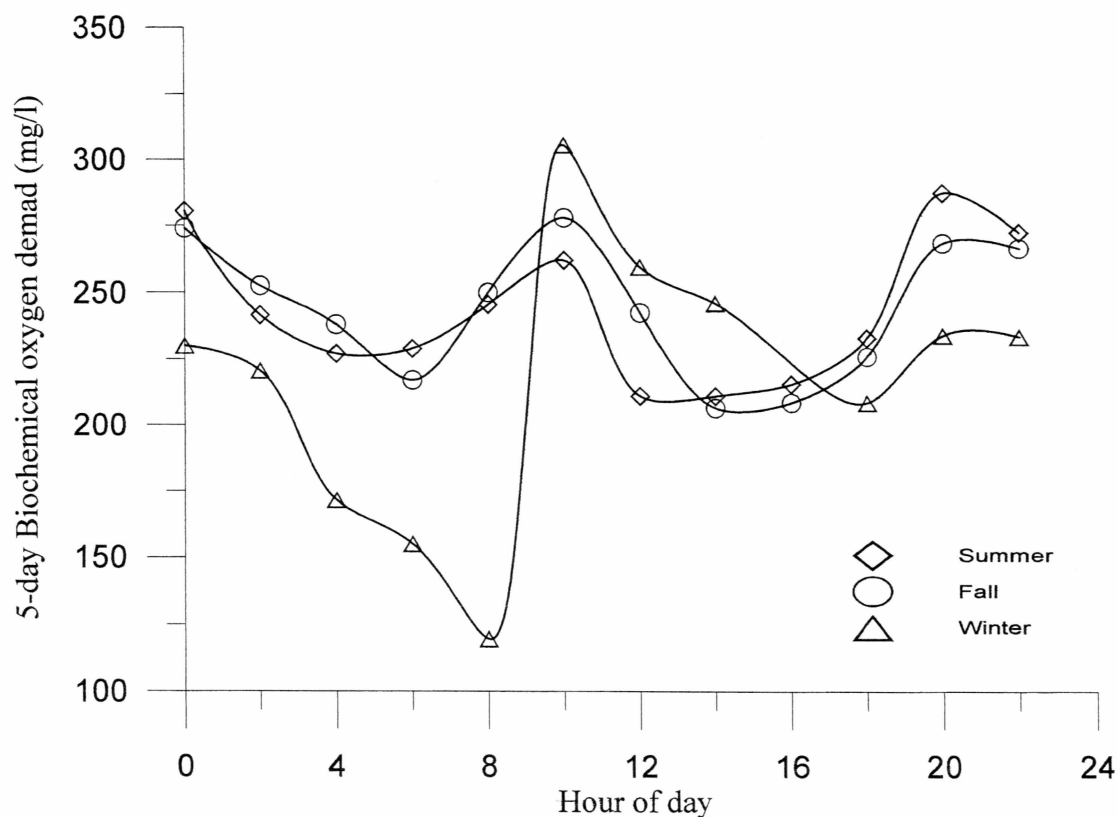


Figure 7: Variation in BOD_5 with hour of day

The BOD_5 loading of the influent waste varied between 105 mg/l and 320 mg/l, which is within the literature reported range of 100 to 350 mg/l (Tchobanoglous et al., 2003). The BOD_5 variations in the winter diurnal flow were much more pronounced. The BOD_5 loading on the summer day was 4325 kg/day, on the fall day was 4272 kg/day, and on the winter day was 3189 kg/day. On two of these days (summer and winter), 20-day biochemical oxygen demand (BOD_{20}) was measured. The BOD_{20} values were measured

to get an understanding of the nitrogenous demand being exerted by the influent. The measured values are indicated in Figure 8.

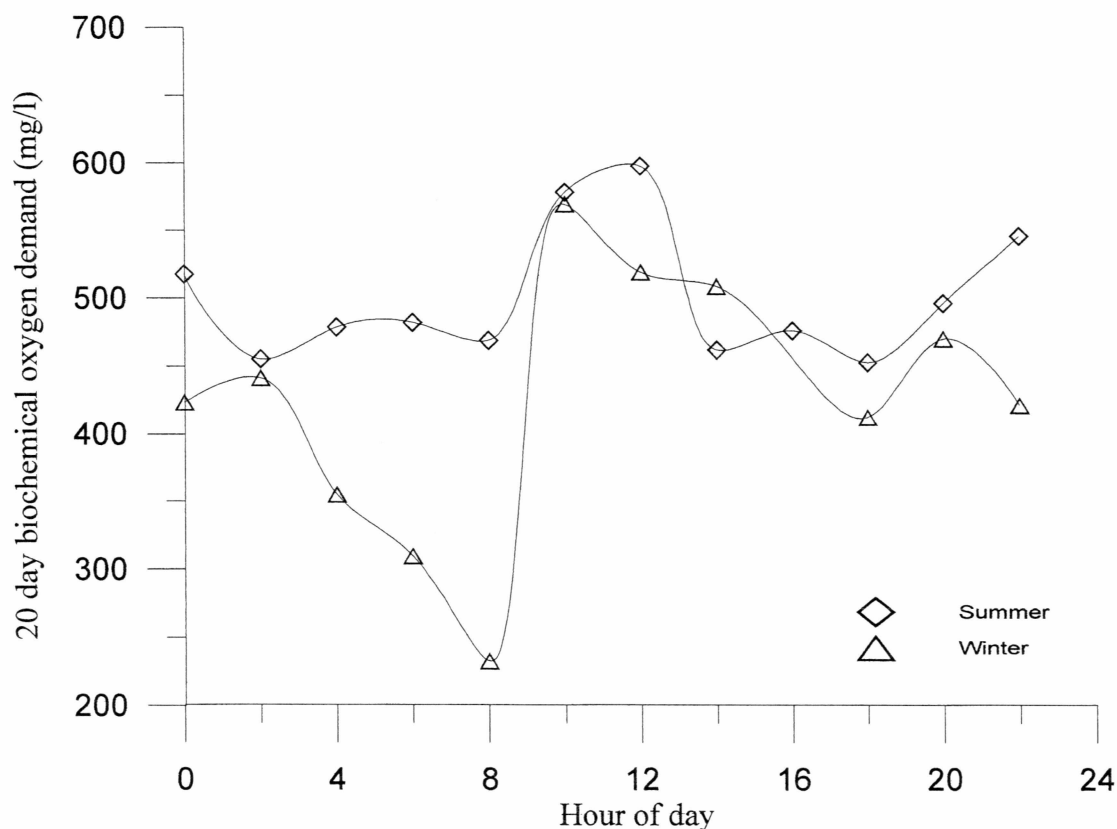


Figure 8: Variation in BOD_{20} with hour of day

The variation in the BOD_{20} followed a similar trend as the corresponding BOD_5 values. The values ranged from 220 to 610 mg/l. These BOD_{20} values show that a substantial nitrogenous demand was also exerted by the influent. The mean value of the ratio of the BOD_5 to the BOD_{20} (ratio of carbonaceous demand to the sum of the carbonaceous and nitrogenous demand) was 0.49 with 95% confidence limits of ± 0.03 . This value matches closely with some literature reported values. Prakasam et al. (2000) report values of 0.5 with 95% confidence limits of ± 0.03 .

An important contributing factor to the high summer and fall flows is infiltration. Infiltration sources include surface water entering the collection systems from a variety of entry points, including service connections, and from groundwater seeping through defective pipes, pipe joints, connections, or access port walls (Tchobanoglous et al., 2003). The effect of infiltration is clearly seen as the diurnal trends for influent flow and BOD₅ do not show peak values at similar times during the summer and fall days (Figure 6 and Figure 7). Diurnal trends for both of these parameters show a similar features during the winter when the effect of infiltration is minimal. Infiltration is a variable part of wastewater, depending on the quality of the collection systems, connections, maintenance, and the elevation of the groundwater compared to the sewer lines (Tchobanoglous et al., 2003). Decrease in flow rate variation during the summer may also be attributed in part to the substantial daylight hours during the summer and fall resulting in distribution of human activity over a longer period of the day.

Variation in influent $\text{NH}_4\text{-N}$ levels with hour of day is shown in Figure 9.

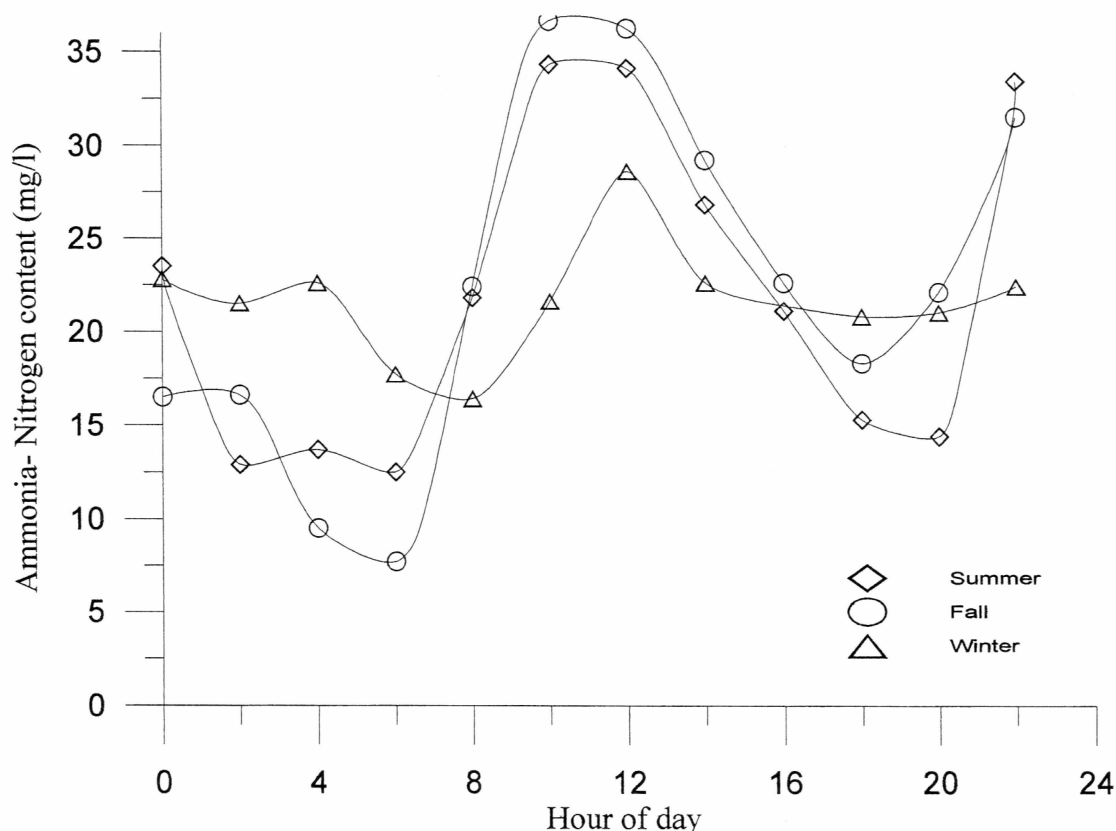


Figure 9: Variation in Ammonia-Nitrogen levels in influent with hour of day

The $\text{NH}_4\text{-N}$ levels in the influent waste vary from low values of 7 mg/l to highs of 35 mg/l. For a domestic facility these values may vary from 12 to 25 mg/l (Tchobanoglous et al., 2003). Values for $\text{NH}_4\text{-N}$ of 120 mg/l or higher were measured several times early in the summer during the initial experimental phase. These high numbers were seen due to the introduction of septic waste into the treatment scheme. The treatment facility does not lower the $\text{NH}_4\text{-N}$ levels before releasing the effluent into the receiving water body. The effluent limits on $\text{NH}_4\text{-N}$ are 5 mg/l on a weekly basis, and 3 mg/l on a monthly basis during the summer. Winter effluent limits are elevated to 10 mg/l and 6 mg/l by the EPA. The treatment facility has been asked to keep a record of the effluent $\text{NH}_4\text{-N}$ by the

Alaska Department of Environmental Conservation (ADEC) since July 2004, with the aim of reducing effluent $\text{NH}_4\text{-N}$ loadings in the future.

Figure 10 shows the variations in TSS with hour of day, on the three sampling days.

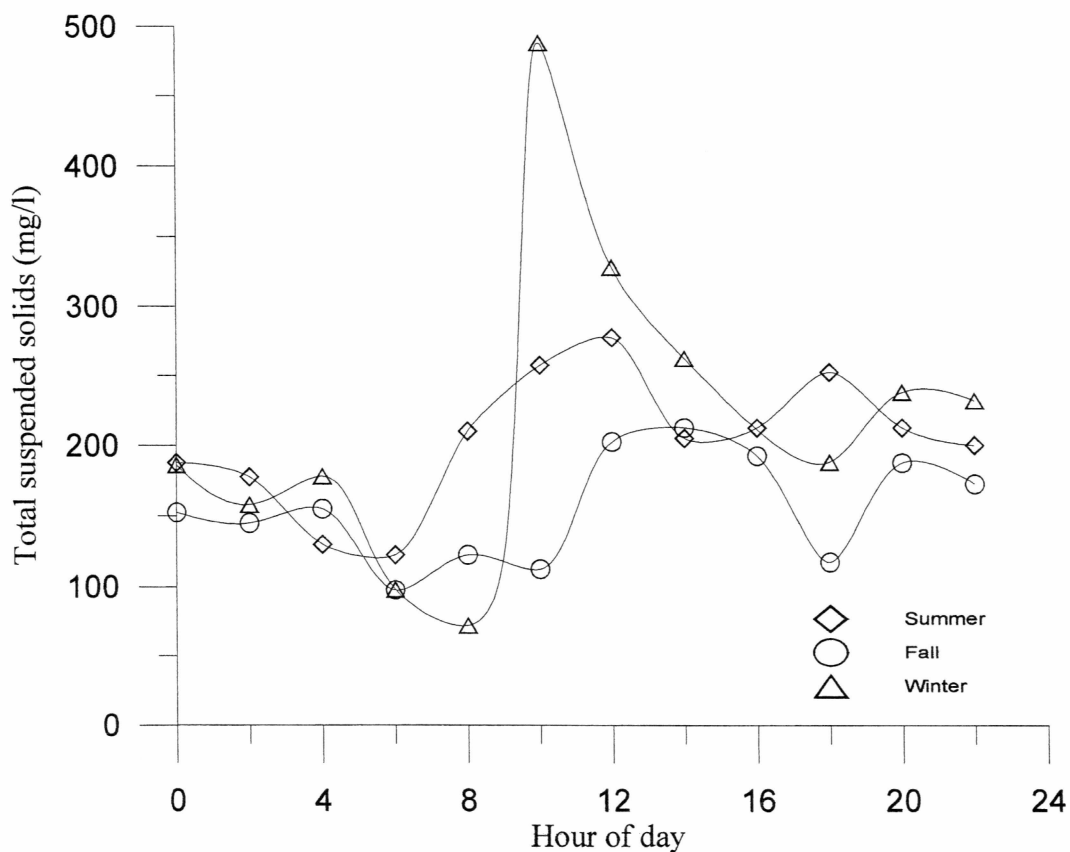


Figure 10: Variations in total suspended solids with hour of day

The total suspended solids (TSS) of the influent varied from a low of 70 mg/l to a high of 500 mg/l. The typical range of TSS is 120 to 400 mg/l (Tchobanoglous et al., 2003). The introduction of septic waste into the treatment scheme leads to high TSS values of 1200 mg/l. Similar to the TSS, the variation in the VSS also has a diurnal trend as shown in Figure 11.

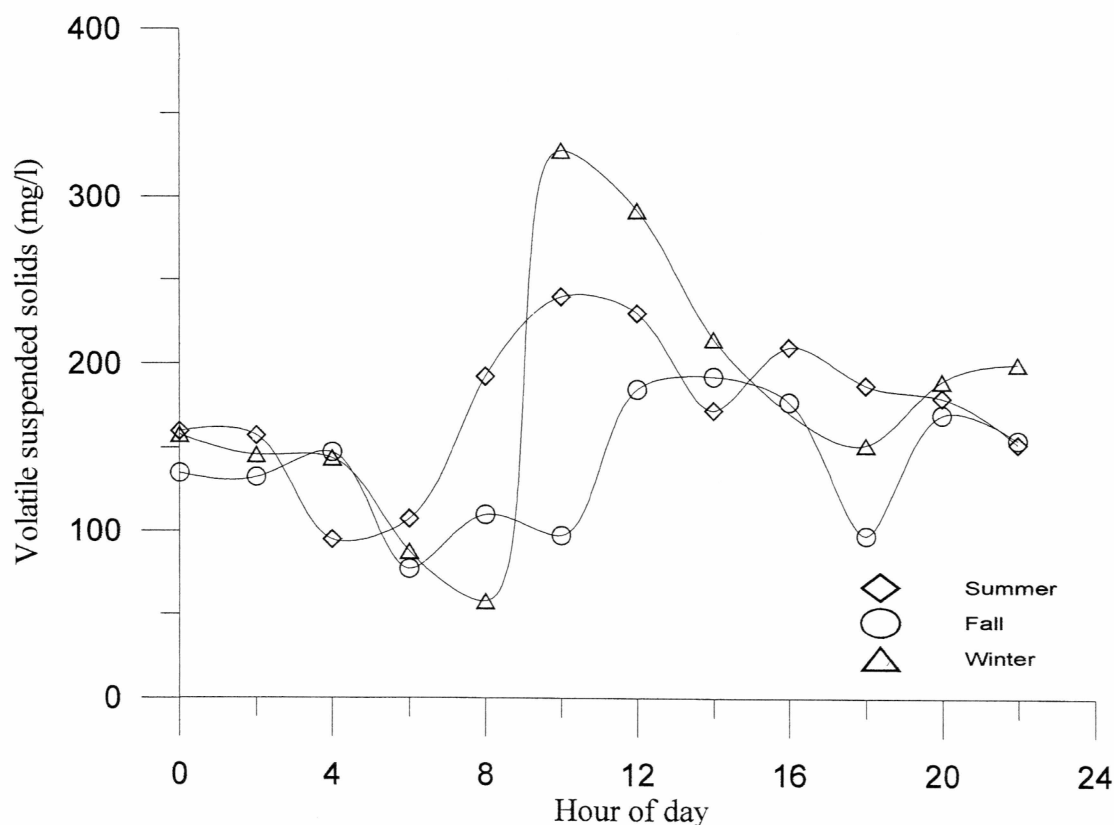


Figure 11: Variations in volatile suspended solids with hour of day

The VSS of the influent varied from 50 mg/l to 330 mg/l. Volatile suspended solids showed similar trends as the TSS, with the winters showing the maximum variation. Figure 12 shows that despite the high range of TSS and VSS values, the ratio of the VSS to TSS (organic suspended matter to total suspended matter) remained almost constant. This result shows that even though the TSS and the VSS values varied substantially from summer to winter, the source of the waste is consistently domestic municipal waste.

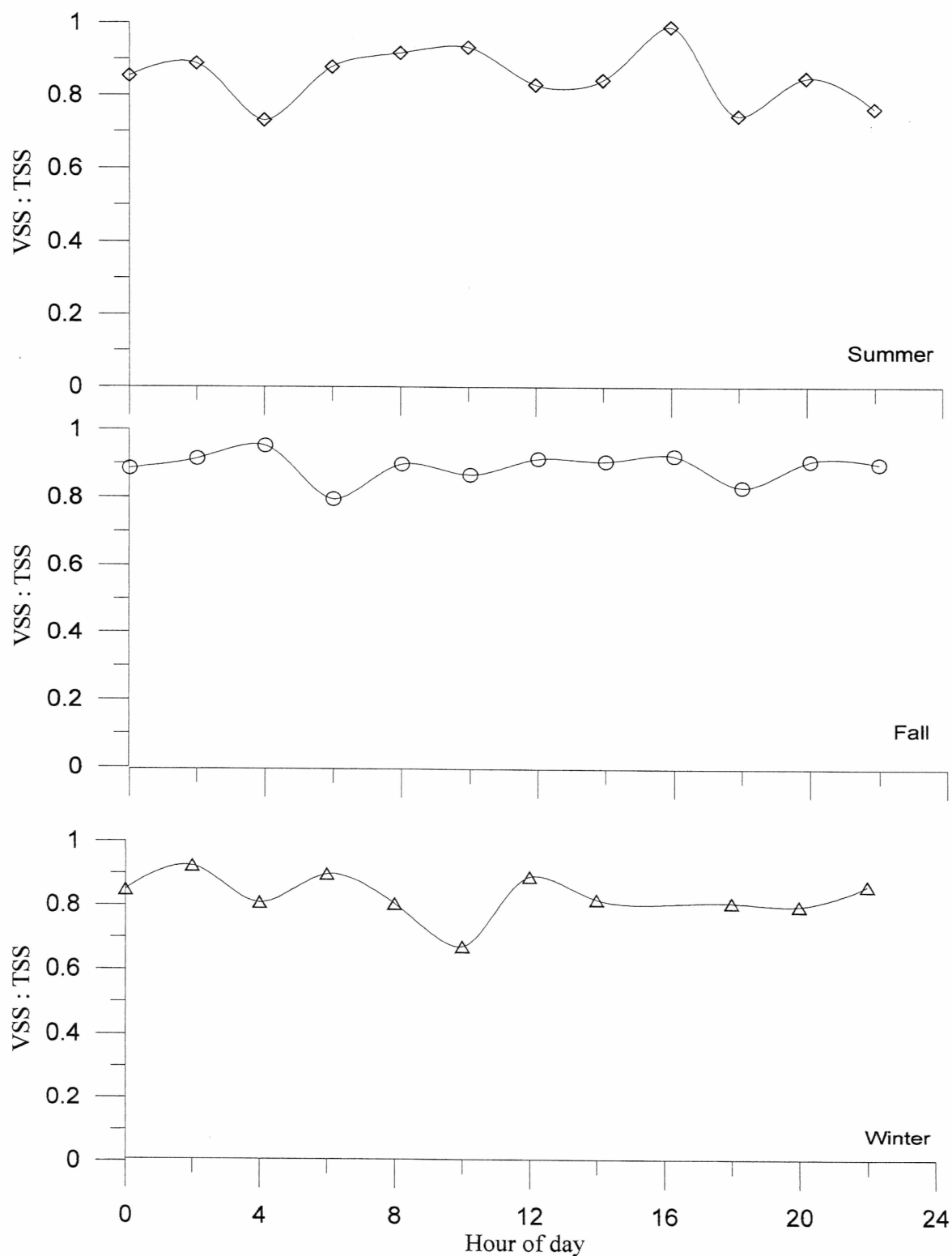


Figure 12: Seasonal comparison of VSS : TSS ratio of influent waste over hour of day

The sludge properties were also measured to determine the functioning efficiency of the treatment scheme. The TSS and VSS for the sludge are shown in Figure 13.

Figure 13 shows that the TSS and the VSS of the RAS remained almost constant. On both the sampling days, a drop in the VSS to TSS ratio was seen early in the morning between 5 am and 6 am and then between 10 am and 1 pm. A drop in the ratio in the early morning may be due to the fact that the BOD₅ loading of the plant during night time was very low. This may result in a famine condition, where the sludge enters into an endogenous phase, thus reducing the number of viable organisms and subsequently reducing the VSS to TSS ratio. The drop in ratio between 10 am to 1 pm could not have been due to low BOD₅ loadings. However, there could be other reasons like presence of toxic material in the influent.

The average TSS value for the sludge was approximately 11,500 mg/l, whereas the VSS was 8,800 mg/l. The ratio of VSS to TSS stayed steady around 0.76-0.8, which was close to literature reported values ranging from 0.8 to 0.85 (Tchobanoglous et al., 2003). These properties were measured to understand the health and activity of the sludge, both critical for the efficiency of the process. Another property that is important is the pH of the influent and the RAS, which are shown in Figure 14. As seen from the figure, the pH for the RAS and the influent varied between 6.5 and 7.2. As a result, the pH in the aerators is approximately 6.8-7.0. This pH value is well short of 8.0, which provides optimum activity conditions for nitrifiers (Grady et al., 1999).

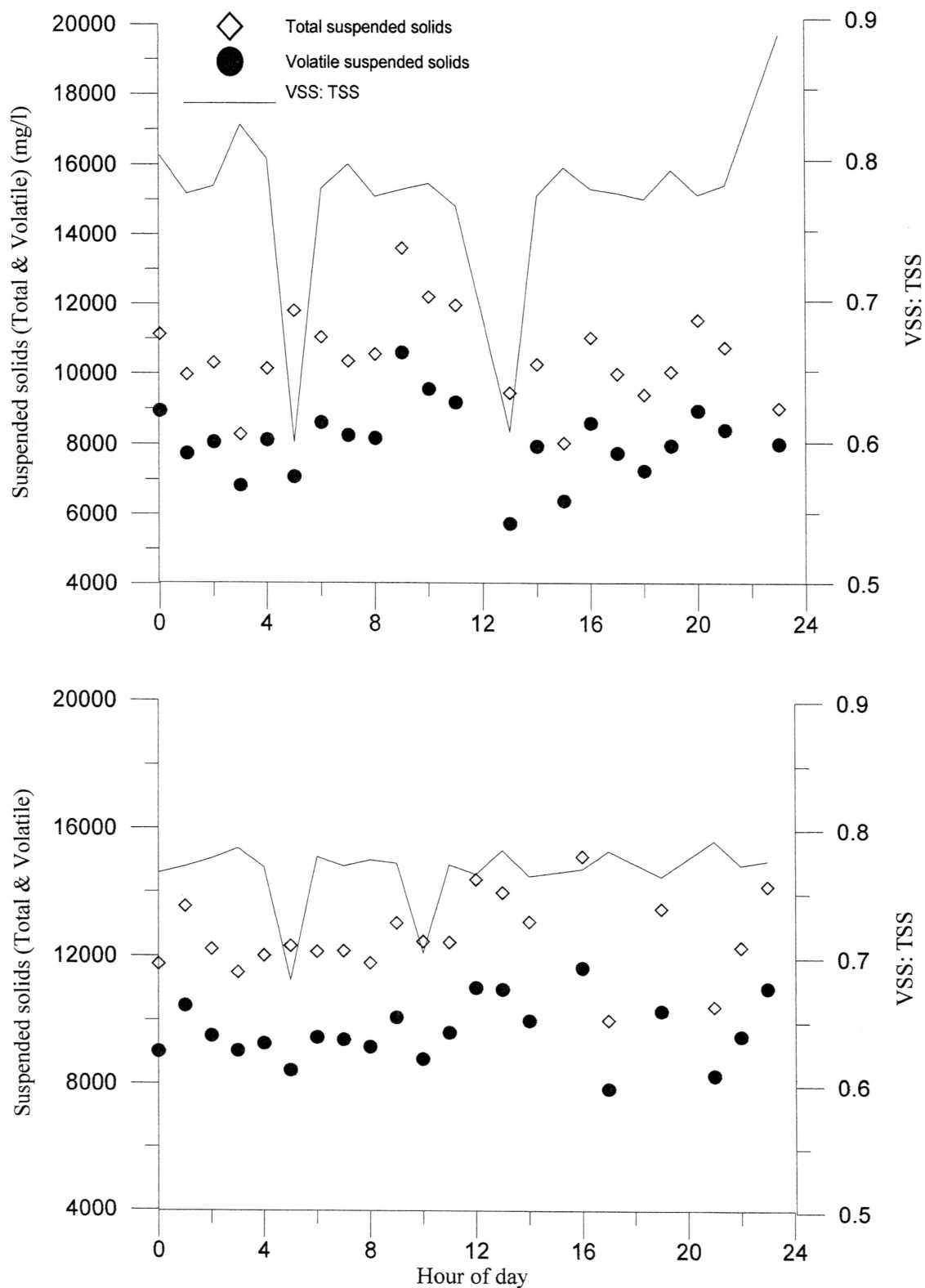


Figure 13: Properties of return activated sludge on sampling days

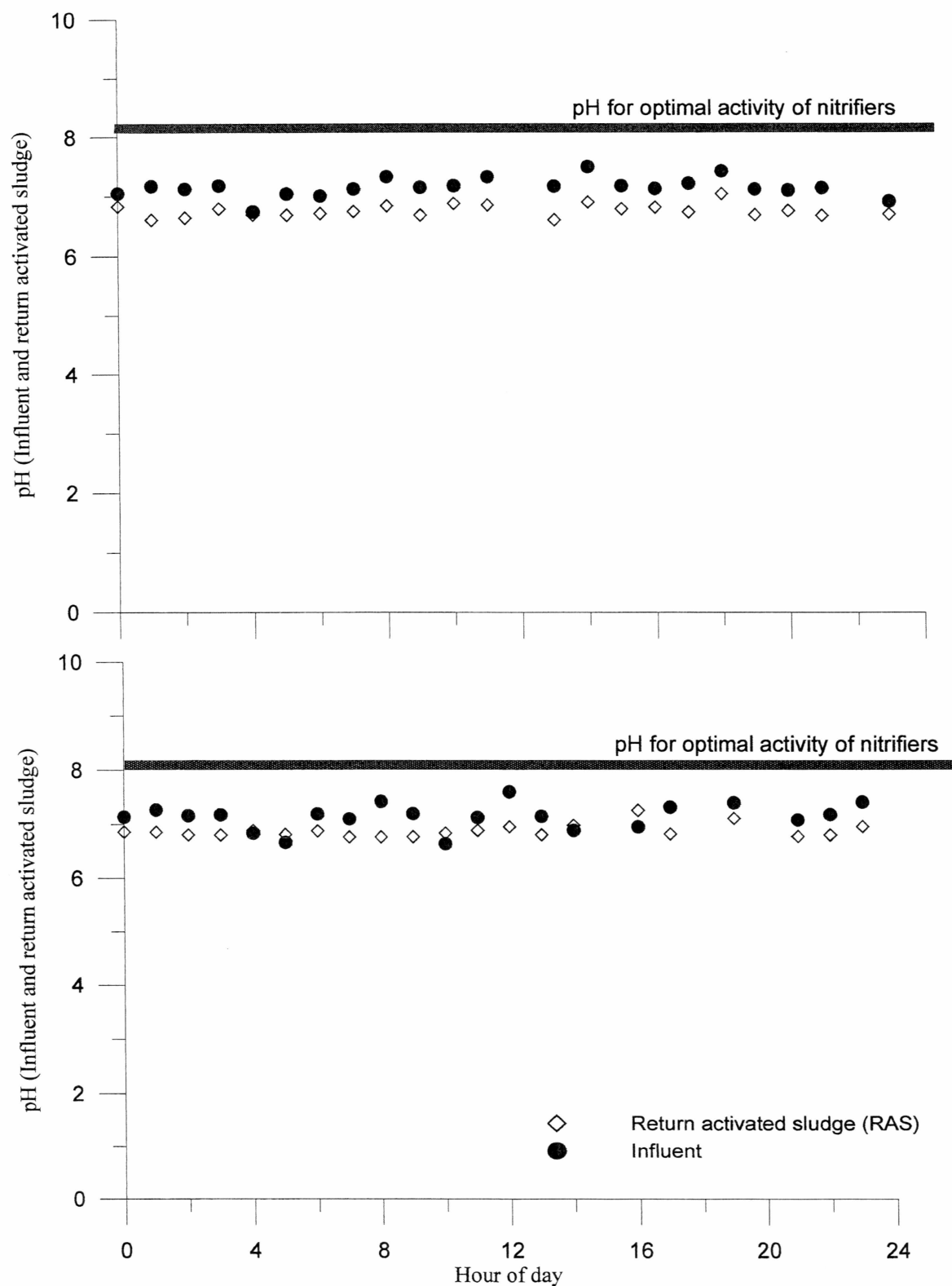


Figure 14: pH of the influent and the pH of the RAS on sampling days.

The following observations can be made from the presented results:

- Seasonal variations were seen in flow rates, BOD₅ loadings, TSS, VSS and the NH₄-N levels of the influent waste.
- Variations were seen over a diurnal cycle for the same parameters.
- The diurnal variations were much more pronounced in winter than in the summer and fall.
- The introduction of septic waste into the treatment facility causes a shock loading in terms of BOD₅, TSS, VSS, and NH₄-N levels.
- The pH of the return activated sludge (RAS) was slightly lower than that required for nutrient removal.
- The influent waste exerts a substantial nitrogenous demand as the ratio of BOD₅ to BOD₂₀ is approximately 0.49.

5. Discussion

As environmental regulations get more stringent, the necessity for advanced treatment options to improve the effluent quality will become obvious. Advanced treatment requirements will in turn demand cost efficient primary, secondary, and tertiary unit processes. As shown in Figure 5, activated sludge aeration is a major plant energy consumer. Up to 55% of the energy costs of a typical WWTF are spent on activated sludge aeration. Several efforts aimed at reducing these expenses have been made towards developing better mechanisms for aeration. Some of these efforts address the fundamental issues of increasing volumetric gas transfer rates into the mixed liquor, such as distributors that create larger surface area between the gaseous and the liquid phase, and pure oxygen (e.g. HPOAS system) to increase oxygen concentration gradients in aeration systems to yield higher dissolution of gas in the liquid phase. Other means of optimizing aeration require making the treatment scheme more adaptable to the dynamic changes in the process parameters. For this purpose, control systems have been designed to adapt the air being supplied to variations in influent and effluent characteristics. It is important to adapt to these variations in Fairbanks, due to the range over which these changes occur. The wastewater treatment plant does take steps to adjust operational parameters by controlling aeration; however, the control strategy being applied could be optimized. To validate the hypothesis that greater control is necessary, aeration optimization with respect to oxygen production was modeled.

The influent characteristics shown on Figures 6 through 12 show definite diurnal trends. An important observation from the results is a comparison between the diurnal trends seen in the summer, fall, and winter. These seasonal variations do affect the operation of the system. The treatment facility was designed to maintain limits on biological performance indicators like F:M. The ratio according to the original design manual of the plant should be maintained between 0.4 and 0.6 lb BOD₅/ lb VSS. To maintain this value, the plant maintains a recycle rate between 40 to 60% of the influent flow. However, calculations based on data collected showed that the F:M ratios were being maintained at a much higher value than the design parameters. The F:M calculated from equation 3 for summer data was 1.0, for fall was 0.8, and for winter was 0.6. Literature indicates that typical values for a high purity oxygen activated systems (HPOAS) range between 0.5 and 1.0 (Tchobanoglous et al., 2003).

During concentrated septic dumping events in the summer and fall, the sludge recycle ratio was increased to avoid the overloading of substrate in the system. Towards late summer, the septic waste was filtered through meshes before it was mixed with the influent line to reduce the suspended solids. Despite this adjustment, the overall system remained overloaded as per the design criteria of the system, with F:M varying from 1.0 to 0.8 in the summer and fall. Even though this condition was not severe, it was sustained for the period of 24 hours in summer and fall. As seen from the results, the flow rate and BOD₅ loadings did not vary drastically over the diurnal cycle. Such overloading can have substantial effect on the health of the sludge. High loadings of the substrate over

sustained periods will result in formation of pinfloc and reduction of filamentous bacteria (Benefield et al., 1980). A filament backbone is necessary for the sludge to provide strength to the floc, and aid in the settling (Grady et al., 1999). In case of pinfloc formation, even though the sludge will have good compaction properties, the lack of strength to the floc will result in poor quality, turbid supernatant exiting the secondary clarifier (Grady et al., 1999). Another important observation of the experimental phase was the sudden spike in the influent BOD₅ values when septic waste was introduced into the facility. Five day biochemical oxygen demand values of up to 500 mg/l were measured during such dumping activity. At a residence time of two to three hours, the aeration scheme would not be able to reduce the organic loading to legal limits. Added to this problem, the concentrated septic dumping activity in the summer as compared to the other seasons makes the summer effluent quality even more vulnerable.

Over a diurnal cycle the effect of the influent characteristics is less severe, since the operator is knowledgeable about the nature of waste entering the facility. However, this does not eliminate the possibility of shock loadings of substrate or toxins to the WWTF. Regular point source samples are collected at different locations in the city of Fairbanks, such as the sewer exiting the city power plant, and the University of Alaska Fairbanks sewer line, to see if the discharge from these facilities meets the pretreatment standards. These regular checks are oriented towards punitive measures in terms of monetary reimbursements for exceeding certain limits.

With respect to the cost efficiency, the measures being taken to meet economic goals are fairly rudimentary. For this purpose, only the aeration scheme will be discussed as it is the most cost intensive operation in the entire treatment facility, especially at the Fairbanks WWTF. The aeration scheme in the wastewater treatment facility has been described in a previous chapter. Oxygen is supplied to the headspace of the first chamber of each of the two aerators by a two inch pipe. The partial pressure, generated by a 90-95% pure oxygen gas, is considered sufficient to result in mass transfer to the liquor. To aid this gas transfer mechanism, turbines have been included in each chamber. The mixed liquor suspended solids are also kept in suspension by the mixing action of the turbines.

At the Fairbanks WWTF, the control strategy with respect to the aeration and oxygen supply is very basic in nature. At different times of the day, namely at 1:00 am, 6:00 am, 5:30 pm, 7:30 pm, and 10:30 pm, the DO levels in the last chambers of the two aeration trains are checked. The set point for this DO level is kept at 1.0 mg/l. If the DO level is found to be lower, the oxygen supply is increased by a set amount. These five DO measurements taken through the day are considered sufficient to maintain effluent standards of 30 mg/l BOD₅, and 30 mg/l TSS per month. Comparison was made between the oxygen that was supplied on the three sampling dates and the actual amount of oxygen required as dictated by the quantity of the effluent and its organic loading. Calculations for the total oxygen required were made based on influent characteristics. While calculating the oxygen requirements, the nitrogenous oxygen demand was ignored. It was assumed that the facility is not equipped for nutrient removal. This assumption is

based on the following observations. As seen in Figure 7, the $\text{NH}_4\text{-N}$ levels in the influent waste vary between 7 to 35 mg/l. Effluent from this WWTF also has a similar $\text{NH}_4\text{-N}$ level indicating that the aeration process fails to implement its reduction.

The fundamental mechanisms involving ammonia in the activated sludge process are ammonification and ammonia utilization. Ammonification involves the release of ammonia nitrogen as amino acids and other the nitrogen containing organic compounds undergo biodegradation. The rate of ammonification will depend on the availability of nitrogen containing substrate and the carbon to nitrogen ratio of the substrate. Ammonification occurs when heterotrophic biomass destroys nitrogen containing soluble organic matter. Hence, the rate of ammonification may be proportional to the rate of depletion of the soluble substrate.

Ammonia can be utilized in a variety of ways: aerobic growth of heterotrophic biomass with ammonia as the nitrogen and electron source (nitrate acts as the terminal electron acceptor), and aerobic growth of autotrophs with ammonia as electron donor. This use of ammonia occurs due to the presence of nitrifiers. Temperature, substrate concentration, dissolved oxygen (DO), pH, and solids residence time (SRT) are a few parameters that affect the removal of nitrogen in a typical activated sludge process (Tchobanoglous et al., 2003).

As shown in Figure 14, the pH of the RAS is approximately 7.0. The nitrifying bacteria are particularly sensitive to changes in pH. Quinlan (1984) presented a plot indicating the effect pH on the activity of the nitrifying bacteria. This plot has been reported by Grady et al. (1999).

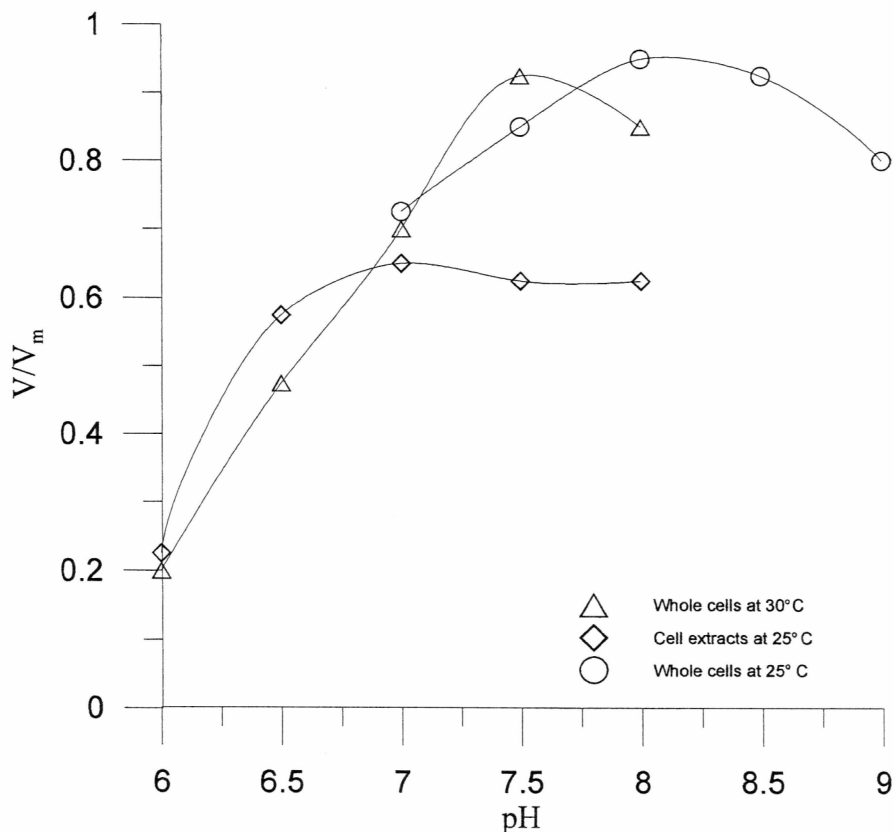


Figure 15: Effect of pH on the maximal activity of *Nitrosomonas* (Grady et al., 1999)

The V/V_m is the ratio of specific growth rate of the bacteria to the maximum specific growth rate. Figure 15 shows the activity of nitrifiers peaks at a pH above 7.5. Ammonium oxidation occurs optimally at a pH of 7.0 to 7.5 and follows the Arrhenius law (Wong-Chong and Loehr, 1975). With reduction in pH, there is a sharp drop in the activity of the nitrifiers. The sludge at the Fairbanks wastewater treatment facility is at pH 7.0. This indicates that the nitrifiers are at an activity of approximately 0.4-0.6.

Literature indicates various equations for the prediction of the nitrifier growth rate. One of the more popularly used equations is the one proposed by USEPA in 1978:

$$\mu_{N,pH} = \mu_{N,M} \times [1 - 0.833(7.2 - pH)] \quad (10)$$

where $\mu_{N,pH}$ is the specific growth rate of the nitrifying bacteria as a function of the pH (g cell/ g cell yield-day), and $\mu_{N,M}$ is the maximum specific growth rate of the nitrifying bacteria (g cell/ g cell yield-day). Equation 10 suggests that at a pH 6.0 there is no growth of the autotrophic nitrifiers. Low pH will drastically retard the nitrification process resulting in no change in the $\text{NH}_4\text{-N}$ levels. This clearly indicates that the low pH of the RAS (pH 7.0) is one of the reasons for little or no change in the $\text{NH}_4\text{-N}$ levels, and hence the absence of nitrogen removal.

The rate of $\text{NH}_4\text{-N}$ removal from wastewater also shows a very strong dependence on the aeration and the DO levels being maintained in the mixed liquor. Dissolved oxygen is the free or chemically uncombined oxygen in wastewater. Nitrifiers are strictly aerobes and they can nitrify only in the presence of DO. Gerardi (2002) reports the manner in which the $\text{NH}_4\text{-N}$ removal is affected by the presence of the DO levels.

Table 2: DO concentration and the nitrification achieved (Gerardi, 2002)

| DO Concentration | Nitrification Achieved |
|-------------------------|-------------------------------|
| < 0.5 mg/l | Little nitrification, if any |
| 0.5 – 1.9 mg/l | Inefficient nitrification |
| 2.0 – 2.9 mg/l | Significant nitrification |
| 3.0 mg/l > | Maximum nitrification |

The DO level in the aeration train is maintained at 1.0 mg/l, which is inefficient for the purpose of nitrification.

A third parameter that affects the functioning of nitrifiers is the wastewater temperature. The rate of growth of nitrifying bacteria increases considerably with an increase in temperature over the range of 8-30°C. *Nitrosomonas* shows an increase in growth rate of almost 10% with every 1°C rise in temperature (Gerardi, 2002). Nitrifiers also show greater activity towards nitrification at temperatures around 25-30°C. The Fairbanks facility does not experience such temperatures; the average influent temperature in summer is 15-16°C, with the winter temperatures being close to 5-6°C. Such low temperatures may significantly reduce the efficiency of nitrification. The maximum specific growth rate is temperature dependent. A detailed report of the dependence of this maximum specific growth rate on temperature has been presented by Randall et al. (1992). Laudelout (1978) shows that for complete removal of nitrogen from an influent of

million gallons per day, the time taken at 10° C is 2.5 times the time taken at 30 °C.

Hence, the influent temperatures are too low to favor any substantial nitrifier activity.

The next parameter that is critical for nitrogen removal in an activated sludge system is the SRT. The SRT for the Fairbanks WWTF was calculated using:

$$X = \frac{SRT}{HRT} \left[\frac{Y(COD_{IN} - COD_{OUT})}{1 + (k_d SRT)} \right] \quad (11)$$

where X is the Biomass concentration in the aerator, SRT is the solids retention time, HRT is the hydraulic retention time, Y is yield coefficient, COD_{IN} is the influent chemical oxygen demand, COD_{OUT} is the same for the effluent, k_d is the death coefficient (Tchobanoglous et al., 2003). The equation was solved for SRT. The following values were used for each of these parameters (Tchobanoglous et al., 2003).

Table 3: Parameter values used for calculating SRT

| Parameter | Values |
|--------------------|---------------|
| X | 3000 mg/l |
| HRT | 0.095 days |
| Y | 0.7 gVSS/gCOD |
| COD _{IN} | 365 mgCOD/l |
| COD _{OUT} | 45 mgCOD/l |
| k _d | 0.1 gVSS/gVSS |

The SRT calculated for the Fairbanks WWTF system by repetitive iterations was 1.5 days. Tchobanoglous (2003) reports that SRT values for a HPOAS system may vary between one and five days. The SRT at the Fairbanks WWTF is within this range. Grady (1999) shows that a HPOAS system with an SRT of two days will have a high effluent $\text{NH}_4\text{-N}$ level, which is consistent with the results seen at the Fairbanks facility. A low SRT means that even though the conditions for the growth of heterotrophic bacteria, which consume soluble organic substrate, may be suitable, the autotrophic bacteria may not be well developed. Typical values of specific growth rate for heterotrophic bacteria are an order of magnitude larger than those for the autotrophic bacteria (Grady et al., 1999). This difference in growth rate means that the SRT required for autotrophic bacteria may be almost an order of magnitude larger than that for the heterotrophic bacteria. Grady et al. (1999) also state that with sufficiently large SRTs the nitrogen removal efficiency approaches 100%, but it also falls rapidly with decrease in SRTs. Tchobanoglous et al. (2003) report that typical SRT values for systems designed for nitrogen removal may range from 3 to 18 days, which is higher than the Fairbanks WWTFs SRT value. Due to the lack of appropriate RAS pH, influent temperature, DO levels, and SRT values, it was assumed that the facility is not equipped for nitrogen, i.e., $\text{NH}_4\text{-N}$ removal. Hence, the nitrogenous demand was not considered while calculating the oxygen demand.

The oxygen required for the mixture of the influent and the return activated sludge in the aeration train can be given as follows (Tchobanoglous et al., 2003):

$$O_2(kg / h) = [((COD_{IN} - COD_{OUT}) \times Q)] - [1.42 \times P_{X,BIO}] \quad (12)$$

where Q is the influent flow rate, COD_{IN} is the influent chemical oxygen demand, COD_{OUT} is the same for the effluent. The chemical oxygen demand is calculated as 1.5 times the BOD_5 . $P_{X,BIO}$ is the amount of biomass produced due to removal of BOD_5 and is calculated as follows (Tchobanoglous et al., 2003):

$$P_{X,BIO} = \frac{Q \times (COD_{IN} - COD_{OUT}) \times Y}{(1 + k_d \times SRT)} + f_d \times k_d \times X \times HRT \times Q \quad (13)$$

where Q is the influent flow rate, Y is the yield co-efficient, COD_{OUT} is the effluent COD, HRT is the hydraulic residence time, X is the biomass concentration in aeration train, k_d is the death coefficient, f_d is the fraction of cell matter forming cell debris, SRT is the solids retention time days. Using these parameters with values reported in Table 4, the $P_{X,BIO}$ was calculated.

Table 4: Parameter values used for calculating $P_{X,BIO}$

| Parameter | Values |
|-----------|---------------|
| X | 3000 mg/l |
| HRT | 0.095 days |
| Y | 0.7 gVSS/gCOD |
| k_d | 0.1 gVSS/gVSS |
| f_d | 0.2 |
| SRT | 1.5 days |

The O_2 demand calculated in equation 12 was calculated by two different approaches. In the first approach, the flow rate and the COD_{IN} were varied according to experimentally measured values to calculate the oxygen required. In the second approach, the amount of oxygen required for the influent waste was calculated using a weighted average of the influent oxygen demand and influent flow rate. This variation in oxygen demand is purely dependent on the flow rate as it is the only quickly determinable parameter. A 25% excess was added to the calculated oxygen supplied by assuming a vent gas oxygen purity of 0.3 (mole fraction of oxygen) (Yuan et al., 1993). The third plot in each graph is the actual oxygen being supplied. In Figures 16, 17, and 18, the amount of oxygen supplied and oxygen required was compared.

The total amounts of oxygen required and supplied are summarized in Table 5.

Table 5: Comparison of oxygen required and supplied on sampling days

| Oxygen | Summer | Fall | Winter |
|--------------------------------|------------------|-----------------|----------------|
| Oxygen supplied | 1034 kg per day | 761 kg per day | 881 kg per day |
| Required: approach 1 | 780 kg per day | 772 kg per day | 553 kg per day |
| Required: approach 2 | 830 kg per day | 820 kg per day | 593 kg per day |
| Average excess supplied | 110.5 kg per day | - 35 kg per day | 309 kg per day |

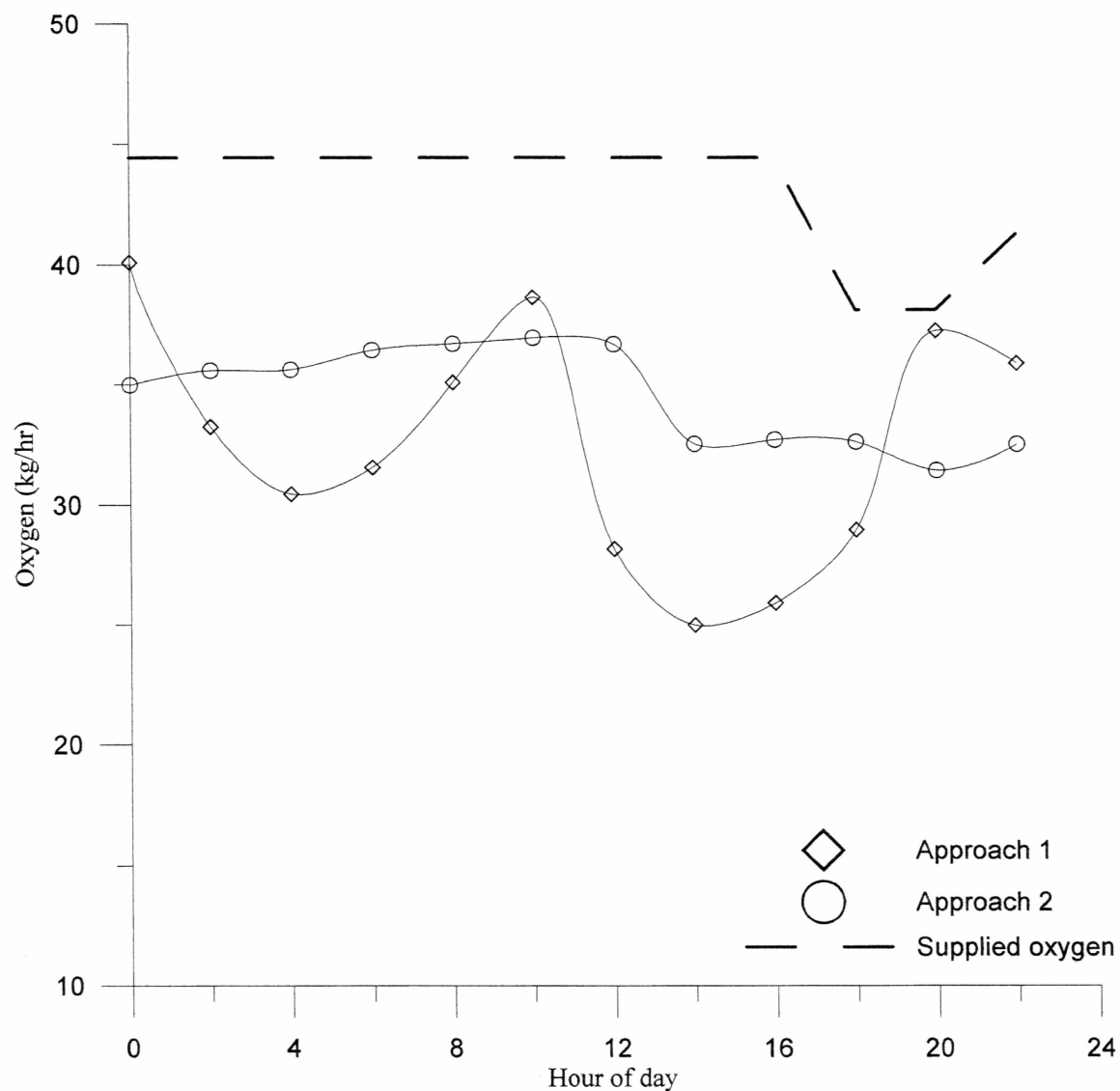


Figure 16: Comparison of amount of oxygen supplied to the amount of oxygen required in summer

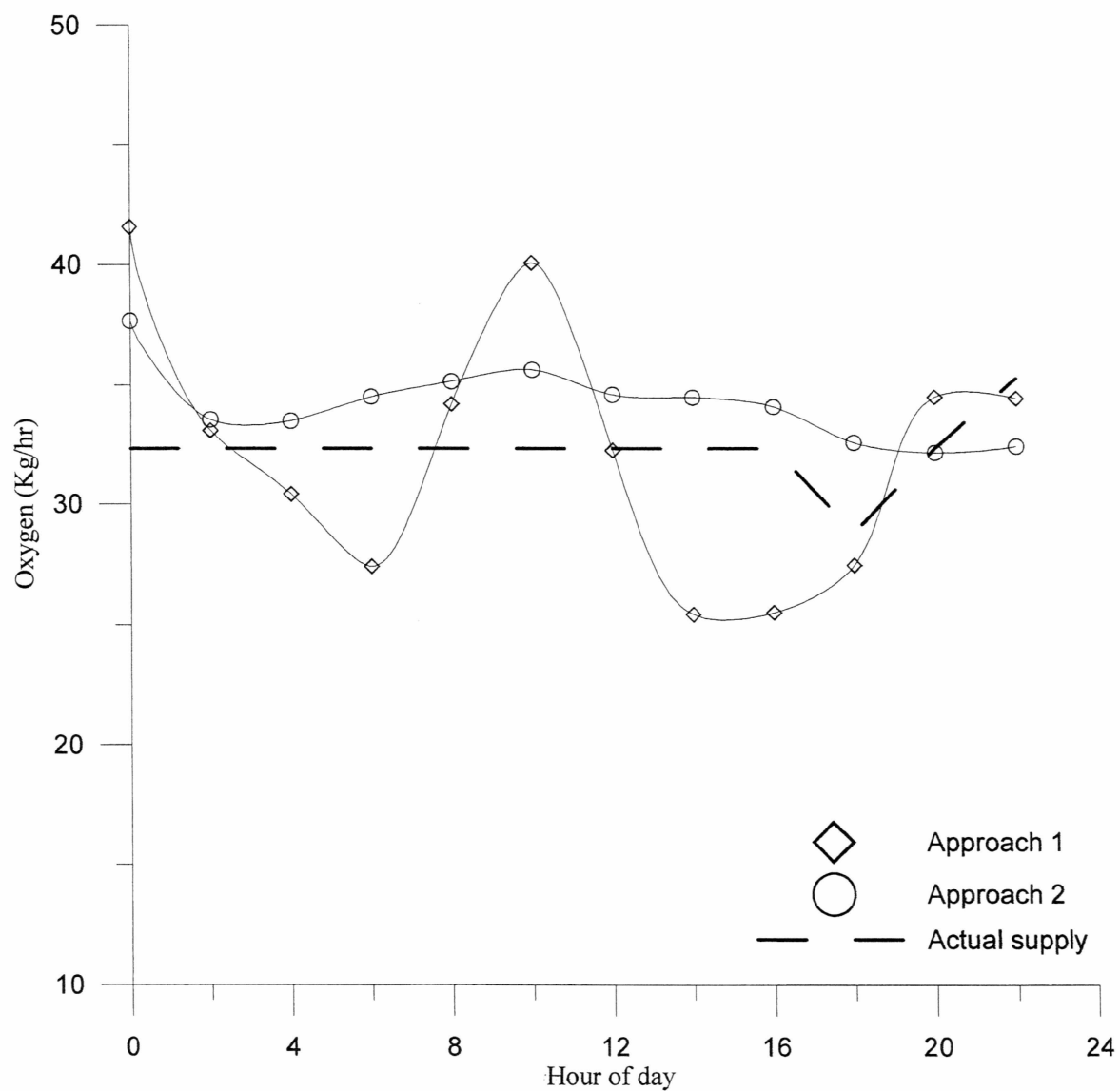


Figure 17: Comparision of amount of oxygen supplied to the amount of oxygen required in fall

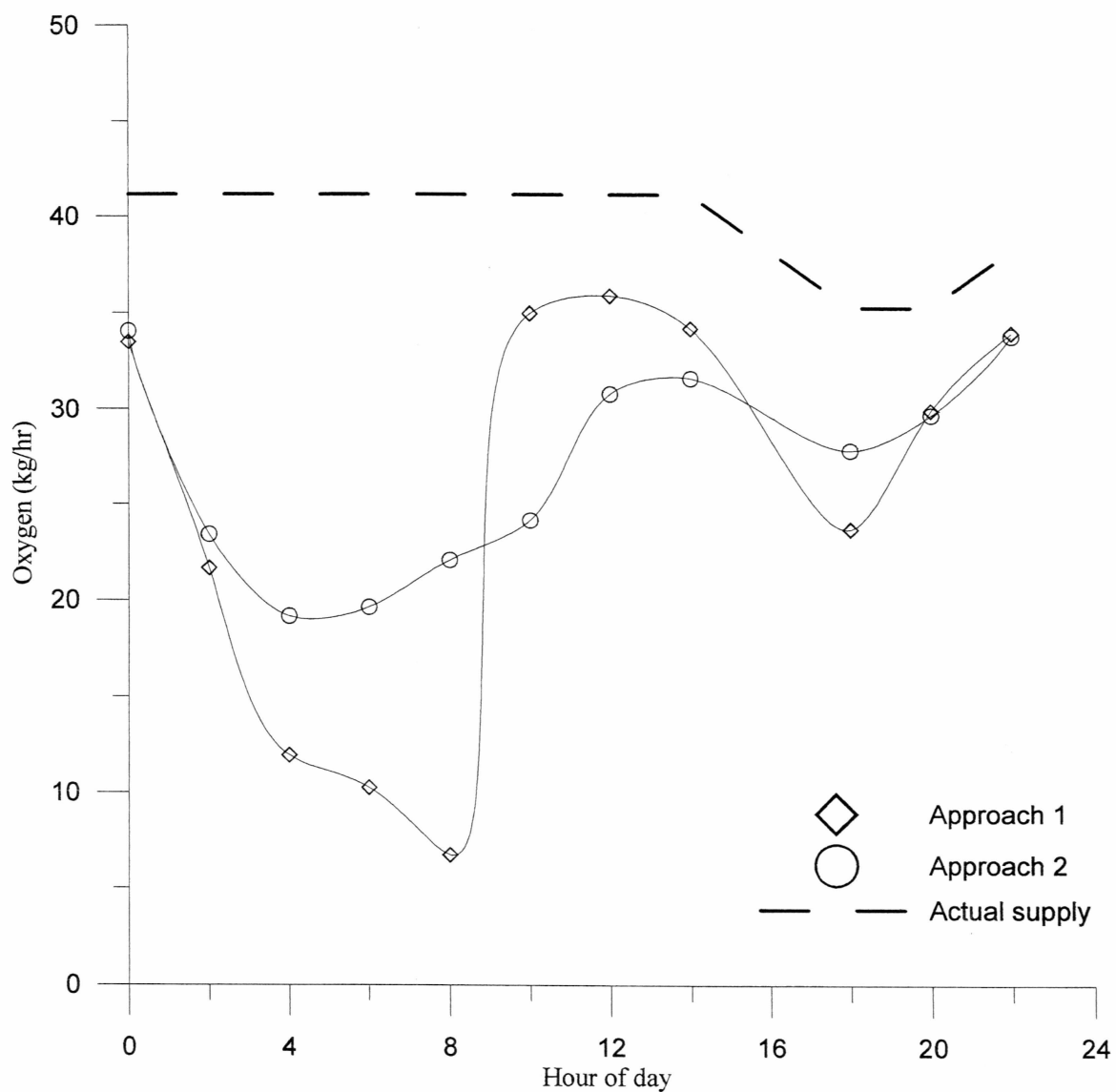


Figure 18: Comparison of the amount of oxygen required to the amount of oxygen supplied in winter

Table 5 shows that the supply of oxygen is in excess in both summer and winter, with the amount of oxygen supplied in fall being lower than the required value. The amount of oxygen supplied during fall was lower than that required, as one of the aerators was shut down for maintenance and the single fully operational aerator was required to treat the entire amount of influent. Hence, the deficient supply is neglected in the further discussion. The trends shown in Figures 16, 17, and 18, make the excesses and deficiency of oxygen supplied clearly visible. The excess oxygen being supplied is much larger in winter. This could be because of the large diurnal variations being experienced in winter. In calculating the oxygen demand the values, the constants were obtained from literature. The yield coefficient was also taken from a literature reported range. Typically for a HPOAS system the yield coefficients are larger, i.e., in the range of 0.6-0.8 (Benefield et al., 1980). The value used in these calculations was 0.7 (Jeppson, 1996). A better solution would be to calculate the yield coefficient. However, the most suitable route for obtaining this value would be logging the solids being wasted. At the Fairbanks facility, the meter used to measure the solids wasted is not accurate, to the point of reporting wastage of solids at times when there is no wasting. The SRT (which could be used along with sampling data to calculate the yield co-efficient) is also not maintained or calculated at the facility, which leaves no option but to assume the yield co-efficient value.

Using these diurnal variations to determine and supply the exact amount of oxygen required could produce almost 35% oxygen savings in the winter and 10.6% oxygen savings in the summer. LOTEPRO Environmental Systems and Services installed the

current oxygen generation system at the Fairbanks WWTF in 1970. They provided an estimate of 450-550 kWh of electricity consumption per ton of oxygen produced. However, the electric efficiency of the system has decreased over a period of 30 years due to mechanical wearing of the system, and the Fairbanks WWTF does not keep a record of the current unit electricity consumption. Assuming a 20% decrease in efficiency, the electricity consumption per ton of oxygen produced will be 660 kWh. The Fairbanks WWTF pays \$0.067 per kWh of electricity consumed. In winter, \$410 can be saved on the electricity consumption for oxygen production per month. An optimal supply of oxygen would also reduce the amount of biomass produced by approximately six tons per month. This translates in reducing the solids handling cost by about \$600 per month. Hence, the monthly savings can be estimated to just over \$1000. This number does not include electricity consumption for mixing, periodic replacement of the gas separation sieves used in the PSA system, and the periodic maintenance costs of the system. Including these items the monthly cost savings could be well over \$1000. The need for a better control system is clearly demonstrated by the excesses in oxygen supply due to the current control strategy.

An optimal control would be anticipatory control of aeration with upstream measurements of the wastewater characteristics as shown in Figure 19. It consists of a respirometer installed upstream of the aeration train. A sidestream from the pretreated influent would be diverted towards an online respirometer, which can help determine the OUR of the incoming influent. Depending on the OUR of the influent, the oxygen being

supplied to the aeration train can be manipulated. The validity of such a system becomes more apparent in medium to large-scale WWTFs.

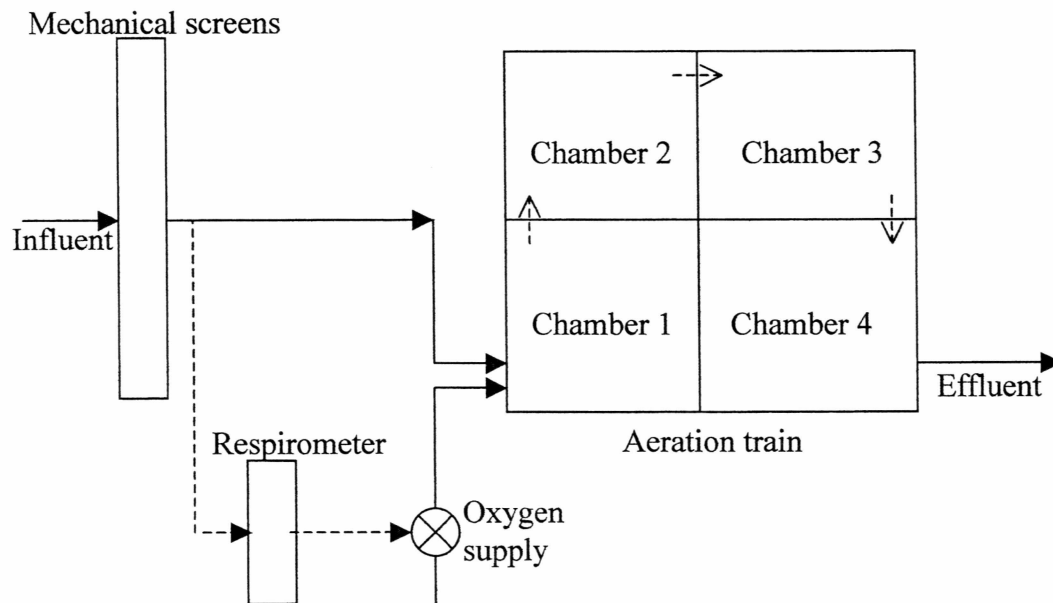


Figure 19: Implementation of the anticipatory control of aeration control strategy

The lack of a primary settler in the Fairbanks WWTF means the influent enters the aeration train within five to six minutes of entering the facility. Hence, the respirometer being used should be able to indicate the OUR of the influent within that short time frame. There are several online respirometers available in the market. Rös (1993) lists the different commercial respirometers as RODTOX apparatus, N-Con COMPUT-OX wastewater respirometer, O_2/CO_2 respirometer, Polumat, VITUKI respirometer, continuous respirometer, electrolytic respirometer, Gilson respirometer, Arthur Technology On-line Respirometer, and BOD-M3 respirometer. The Arthur Technology On-line Respirometer has been applied in similar applications. This system has been applied with varying degrees of success. Arthur and Arthur (1994) reports 15-40%

savings in facilities with such an application. Riegler (1987) reports that the BOD-M3 respirometer is able to predict the oxygen demand being exerted by the influent within 3 minutes. This respirometer requires calibration with respect to the unique wastewater treatment facility parameters, specifically the BOD₅ and the OUR of the wastewater using the RAS available in the WWTF. Wong and Smith (1992) commented that during the use of a new RAS, the system required calibration and the correlation between BOD₅ and its appropriate parameters must be updated. This implies that such a correlation must be established uniquely for every different facility, on the basis of sheer variety in the type of wastewater and the type of RAS. This uniqueness can be seen as a drawback of this approach. However, for a respirometer like the BOD-M3, which takes only 3 minutes to give a reading, the exercise of developing a correlation may be very short and hence manageable. Correlations between different output parameters like OUR (Arthur, 1984), specific oxygen uptake rate (SOUR) (Wong and Smith., 1992) and BOD₅ have been reported to show almost 95-98% accuracy, and hence are considered reliable.

The application of an online-calibrated respirometer would show definite advantages. Implementation at the Fairbanks facility would require certain special considerations. The lack of a primary settler implies that samples must be collected before or after the bar screens. Due to lack of the primary settler, the influent entering the aeration train has a high value of suspended solids. The on-line respirometer must be able to deal with these large values. Many respirometers depend on magnetic stirrers for mixing. These magnetic stirrers are not able to maintain homogenous conditions when the system is overloaded

with sludge (microorganisms). The respirometer of choice must ensure homogenous mixing conditions and stirrer stability at high rates of mixing. Accurate predictions are important when correlating the OUR to the BOD_5 value. Several respirometers give good correlations over a time frame of half hour to 4 hours. The lack of a primary settler also means that the influent reaches the aeration train within five to six minutes of entering the plant. The respirometer must be quick enough to predict an oxygen demand value within this time frame without compromising on accuracy. The BOD-M3 respirometer, with the ability to give accurate predictions in three minutes, is a good solution to this problem.

Another special consideration is the strain or culture of bacteria that would be used in the respirometer. The microbial mass being utilized in the respirometer should be able to handle food overloading of the system during events of septic dumping. The accuracy of correlation between OUR and BOD_5 should be checked under substantial high loadings. The introduction of septic waste can be toxic to the respirometric culture, and hence disturb the set calibration. Wastes like septage and deicing liquid from the airport contain toxic components, which may inhibit the activity of bacteria or even kill them. Usually the RAS from the specific plant is the best solution as it is easy to replace. The temperature of the influent waste may vary from 6-16°C depending on the season. This variation means reduced activity on the part of the bacteria. Most of the respirometric experiments conducted and reported in literature are at room temperature or higher. Correlating OUR and BOD_5 is not difficult as long as both of these values are measured at 20°C. Winter temperatures of influent wastewater may sometimes be as low as 6°C.

The low temperatures are a substantial challenge considering the importance of short time frame correlations. These factors must be given special attention while employing a respirometer at the Fairbanks WWTP.

As mentioned above, the application of such a system would have a three fold benefit: (1) help meet legal discharge requirements despite possible shock loadings, (2) predict the oxygen requirements in the event of the introduction of septic waste into the treatment scheme, and (3) realize oxygen savings can be realized in the production and supply. As the city of Fairbanks grows and the WWTF serves a larger population, the application of such a control strategy to optimize on oxygen use would become a very attractive option.

6. Conclusions

The following conclusions can be made about the Fairbanks WWTF, based on the results from this project:

1. The diurnal variations in the influent wastewater characteristics are very substantial in the winter, based on a single November date.
2. The introduction of septic waste increases the wastewater loading by a large amount and, thus, could disturb effluent quality standards if its oxygen requirement is not predetermined.
3. The treatment scheme in its current operating parameters, including sludge health and SRT is not equipped for nutrient removal. Hence, reducing $\text{NH}_4\text{-N}$ levels in the effluent is improbable without a specific nutrient removal goal, like maintaining higher SRTs, etc.
4. The aeration control strategy being implemented at the treatment system is not optimal, as it results in excess oxygen production and supply of up to 35% in winter.
5. Implementation of an upstream BOD_5 measuring device would help control the oxygen being produced and supplied. This would help avoid production and supply of excess oxygen.
6. Online respirometers like BOD-M3 would provide a good option for the anticipatory control of aeration in the Fairbanks WWTF.
7. The application of a respirometer at the Fairbanks WWTF would require special consideration for high TSS in the influent, high strength septic waste introduction

in to the influent line, developing correlations between BOD_5 and OUR at low temperatures, and making predictions in five to six minutes.

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